WATER QUALITY, CATCHMENT IMPERVIOUSNESS AND WATER SENSITIVE URBAN DESIGN IN A SMALL URBAN STREAM IN HELSINKI, FINLAND

ELLIOT STUART

UNIVERSITY OF HELSINKI
Department of Environmental Sciences
Master's Degree Programme in Multidiciplinary
Studies on Urban Environmental Issues

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Tiivistelmä – Referat – Abstract

The primary characteristic of urbanisation is the addition of hard surfaces to catchments, which affects water and habitat quality in urban streams and alters natural hydrological processes by reducing infiltration, evapotranpiration and efficiently conveying storm runoff to streams, gathering a variety of urban polluants along the way. This is typical of the 'urban stream syndrome'. Catchment imperviousness (especially Effective Impervious Area or percent connectivity) can be used as one of the primary indicators of the severity of this phenomenon.

This research was initiated through a collaboration between the City of Helsinki and the University of Helsinki to determine the baseline water quality of Hakuninmaanoja, a small urban stream in Helsinki, Finland, and the imperviousness of its catchment, where a pilot ecological housing development 'Kuninkaantammi' (KUNTA) will be built beginning in 2013. The purpose of the project is to assess the current characteristics of the catchment prior to the development in the headwaters of the stream. An automatic water quality monitoring station was built on the lower part of the stream approximately 200m upstream of its junction with Mätäjoki, the second largest river of Helsinki.

Water Sensitive Urban Design can be used as part of a holistic stormwater treatment train to limit newly created imperviousness, and minimise the connectivity of the necessary remainder, allowing stormwater runoff to be reused, infiltrated and treated through soil media, or slowed down enough to attenuate the urban hydrograph. Some of these features such as raingardens, green roofs and detention ponds will be included in the KUNTA development for this purpose.

A detailed calculation of catchment imperviousness was completed via field survey and land use categorisation methods. Total Impervious Area (TIA) was determined to be 22%, Effective Impervious Area 15% and catchment wide runoff coefficient given by land use categorisation method to be 0.32. TIA is expected to increase to 30% following development of KUNTA, however EIA is not expected to increase in proportion with TIA due to planned Water Sensitive Urban Design features.

Yearly runoff volumes based on each method of calculating imperviousness were estimated, as well as for the future following KUNTA development. Water quality in the stream currently is quite satisfactory in relation to other streams in Helsinki, however the urban stream syndrome is already evident with particular concern regarding temperature, sediment and peak flow fluctuations.

Effective Impervious Area should be used in urban planning of new and existing developments rather than TIA because it will give much greater accuracy of runoff volumes and infiltration rates by taking into account unconnected impervious surfaces. Strengthening local solutions to reduce connectivity should be a municipal priority. Water quality monitoring will continue at the site until after KUNTA has been built, and further research should focus on determining the technical performance of stormwater Best Management Practices (BMPs) at the site.

Avainsanat – Nyckelord – Keywords
Urban Stream, Effective Impervious Area, Total Imperviousness, Water Quality, Water Quantity, Water Sensitive Urban Design, Stormwater Management, Runoff, Urban Planning, Kuninkaantammi

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1. Project Description

This project is a geographically focused, observational study of a second order urban stream and its catchment in the northern suburbs of Helsinki, Finland. The project has arisen out of the necessity for an understanding of the ecological, biological, and hydrological changes that are may occur to both the Hakuninmaanoja stream and the downstream Mätäjoki river (hereafter simply Hakuninmaanoja and Mätäjoki) as a result of the planned development of the Kuninkaantammi area. The development will be located around the headwaters of Hakuninmaanoja. The Kuninkaantammi (hereafter KUNTA) development, initiated by the City of Helsinki and private investors (two-thirds public, one-third private), is a pilot project for green urban design in large housing developments in Helsinki, and the success or failure of different methods, (in particular of stormwater management) will determine their later use in much larger developments, such as the eastern area of Sipoo.

The KUNTA development is projected to have an area of one hundred hectares, and will house approximately five thousand people.

This project has three central activities:

<u>Water quality monitoring</u>

Hypothesis*:* Water quality will exhibit a range of changes following rain events and activities upstream.

Research questions:

a) What is the water quality of Hakuninmaanoja currently, and what is it likely to be following the development of the KUNTA project?
b) How does water quality change throughout the year?
c) Does a first flush effect exist, even in such a low-density area?

d) Are there any other discernible patterns, such as certain pollutants consistently higher than others?

Accurate measurement of Total Impervious Area (TIA) and Effective Impervious Area (EIA)

Hypothesis: EIA is a more useful figure of catchment imperviousness and indicator of stream health than TIA.

Research questions:

a) What are the percentages of EIA and TIA in the catchment, and what are they estimated to be following development?
b) What are the benefits, challenges and limitations involved in field surveying EIA?

Water Sensitive Urban Design in Finnish conditions

Research questions:

a) How can EIA be reduced, with regard to Finnish conditions?
b) Are the Best Management Practices (BMPs) in the KUNTA plans likely to be effective in mitigating stormwater issues?
c) What aspects of WSUD can be replicated successfully in Finnish conditions?

1.1. Introduction

Urbanisation is a process occurring globally in many cities as a result of population growth, higher standard of living and improved mobility, and is leading to large-scale land use change from rural/agricultural to urban. As of 2010, over 50% of the world's population lives in urban areas. Between 4000 and 8000 square kilometres of land are converted to urban land use globally each year

(Schueler 2000b). Much of this development takes place on the urban fringe, however there is also a concurrent process of a shift towards higher density living within the existing urban area, putting more pressure on an already strained environment. Urbanisation leads to increased impervious surfaces (buildings, roads, parking lots etc.), increasing runoff to stormwater pipes and overland, whilst reducing natural pathways for storage, infiltration, and groundwater recharge, and altering catchment hydrology and channel dimensions (Li and Davis 2009). Urban runoff often contains many pollutants of physical, chemical and biological origin from the urban area as a result of both anthropogenic and natural processes. Compounding this is the alternate side of urbanisation: a decrease in forested, wetland or other natural areas that both mitigate flooding and treat stormwater in situ.

Stormwater management in the developed world has evolved significantly since the 1950s, when the focus was on moving the largest amount of water away from the city as quickly as possible (Brabec, Schulte & Richards 2002), to today where the water quality and quantity impacts of urbanisation are recognised, and are socially visible and politically contentious, and thus attempts are being made to mitigate problems and modify urban design. This goal is pursued today in a variety of ways, at both the local and catchment scale. At the local scale in individual housing developments, many cities are researching and applying Best Management Practices (BMPs), and Water Sensitive Urban Design (WSUD), the latter a term used primarily in Australia, but known as Low Impact Development (LID) in the United States and elsewhere (hereafter WSUD) (Roy *et al.* 2008). At the catchment scale, the concept of imperviousness holds much promise as a critical tool that can integrate the often multidisciplinary nature of urban stream and stormwater management.

Cold climates present unique challenges in stormwater management, such as issues relating to poor performance of BMPs through frozen soil and reduced biological activity in bioretention media (Roseen *et. al.* 2009; Oberts, Marsalek & Viklander 2000), unique soil and water pollutants (such as de-icing salt and chemicals) which lead to high spring loading, as well as snow dumping and high contamination of snow from urban pollutants accumulated over an entire winter season.

1.2. The concept of imperviousness in urban hydrology

Impervious surfaces are defined here as "any material which prevents the infiltration of water into the soil" (Arnold & Gibbons 1996: 1). This includes roads, buildings and parking lots, but also pedestrian footpaths, bike paths, gravel driveways & forest paths, compacted soil, and even bedrock outcrops.

Clearly, in a very large river catchment such as the Amazon River, one or even three cities will not constitute a very large fraction of imperviousness from the total land area. Large catchments are more affected by larger-scale processes such as land clearing, dam building and climate change. Consequently, the concept of imperviousness is much more applicable to smaller sub-catchments within urban areas, where local streams are likely to be impacted by non-point source runoff.

The process of urbanisation increases the area of impervious surfaces. Reduced infiltration increases total runoff and peak flows to streams (Fig. 1), while leading to drying of urban soil and lowering of groundwater levels (Fig. 2). Urban runoff often contains high concentrations of urban pollutants such as suspended sediment, heavy metals, polyaromatic hydrocarbons (PAHs), nutrients such as nitrogen and phosphorus, hydrocarbons and organic carbon (Goonetilleke & Thomas 2003; Allan 2004).

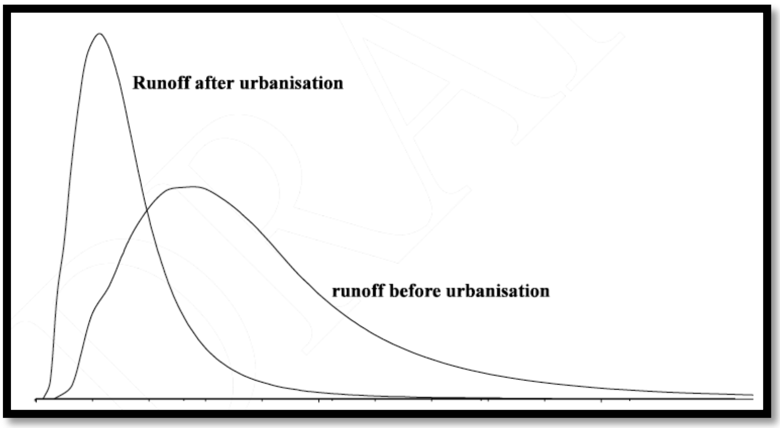


Figure 1. Runoff hydrograph before and after urbanisation. Source: Goonetilleke & Thomas (2003).

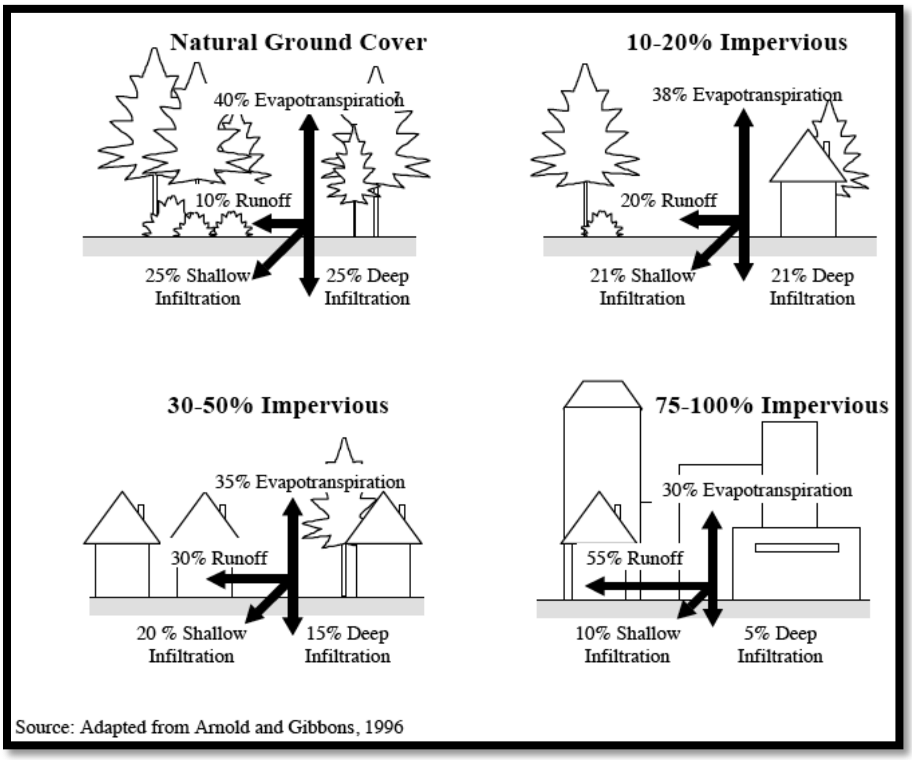


Figure 2. Relationship of imperviousness to runoff and infiltration. Source: US EPA 1999.

The development and growth of the city is a process that is driven by many different factors, and the mitigation of problems requires the cooperation of many different disciplines involved in this process, such as urban and social planners, engineers, community groups, ecologists and resource managers, and politicians. This kind of multidisciplinary cooperation requires a unifying concept that can be quantified, measured and predicted accurately. Catchment imperviousness is the primary manifestation of the city on the natural world, and as such it has several qualities that make it a useful multidisciplinary indicator of environmental and stream quality (Schueler 1994; Brabec, Schulte & Richards 2002):

1) It is arguably the primary characteristic of urbanization;
2) It can be relatively easily measured, temporally (in modeling of future developments and growth trajectories) and spatially (across cities all over the world);

3) Although it doesn't directly generate pollution, research suggests a link between impervious surface and the hydrological and chemical changes that degrade water quality and aquatic habitat;
4) Impervious surfaces that are directly connected to the stormwater infrastructure transport pollutants directly to waterways through pipes;
5) Impervious surfaces prevent pollutants from being filtered through the soil before reaching ground/surface waters.

Arnold & Gibbons (1996) suggest that imperviousness can be a more cost effective and feasible tool for planners than gathering expensive technical information on pollutant loads, utilising hydrologic modeling (eg. USDA TR55 (US Dept. of Agriculture), EPA S.W.M.M, and US Army Corps of Engineers STORM and HEC-1), or analysing and applying research on the effectiveness of various best management practices to local situations.
However, despite the impact of imperviousness on urban streams and its clear usefulness in planning applications, most new developments are undertaken with limited or no calculations of current or projected imperviousness and the potential effects on the catchment (Brabec, Schulte & Richards 2002).

The concept of imperviousness has also been researched for use in planning applications to balance the pervious and impervious areas of a specific development or of the catchment as a whole in order to maintain the biological integrity of the receiving waters. This concept can also be used to define rankings of stream health to be used in planning for prioritizing works in those watersheds where there is the most promise for rehabilitation, for example, 'protected' (<10% impervious), 'impacted' (10-30% impervious) and 'degraded' (>30% impervious) (Schueler 1994; Brabec, Schulte & Richards 2002). Early research in this area has indicated that more than 10 – 15% imperviousness led to a measurable decline in water quality (Schueler 1994), however results have been highly variable and location specific, with the study by Yang *et al.* (2010) suggesting that 3 – 5% imperviousness is a threshold beyond which stream regime alterations become statistically significant.

The connectivity of impervious surfaces within the urban fabric is distinct, and can be described in two ways. Firstly, Total Impervious Area (TIA) refers to all impervious surfaces within a given catchment (roads, roofs, parking lots etc.), including those termed "non-effective impervious surfaces" which are not directly connected to the stormwater network and which drain to pervious ground, such as driveways which drain to lawns (Brabec, Schulte & Richards 2002: 505). Effective Impervious Area (EIA) is only those impervious surfaces that are hydraulically connected with pipes or drains directly to the stormwater network and then to the nearest stream or water body. With EIA almost 100% of runoff will reach the water body, whereas with TIA some non-effective impervious surfaces will drain a portion of stormwater, depending on slope, soil, and ground cover (Brabec, Schulte & Richards 2002).

The difference between the two types of imperviousness (TIA & EIA) is important when making catchment analyses and applying results to urban planning, and a common problem in this field is the lack of distinction between the measurements, or faulty methodology used to calculate them. If only TIA is used, then runoff volumes, peak flows and infiltration rates may be overestimated, and the predicted changes in runoff due to increasing imperviousness may be smaller (Brabec, Schulte & Richards 2002). It is thus important to use EIA rather than TIA in modeling to avoid these issues, and also to standardise measurement to ensure appropriate transferability of results. This would help to reduce site-specific results, as well as increase statistic significance in results as related to land use. Furthermore, there is evidence that gravel driveways and bare soil, which are not traditionally thought of or calculated as impervious surfaces, allow much less infiltration than natural fields or forested areas (Brabec, Schulte and Richards 2002). This again brings into question the methodology used to calculate imperviousness, and the need to standardise it.

The other measurement critical to catchment imperviousness modeling is how to define a degraded stream, which can be described via biotic or abiotic means. The most common biotic measurement is the Index of Biological Integrity (IBI) described by Karr (1987, in Brabec, Schulte & Richards 2002; Allan 2004). This index measures aquatic species' richness & composition, local indicator species, fish abundance and diversity. Abiotic definitions of stream health are mostly individual variables of physical or chemical nature, such as water volume, suspended solids, heavy metals, channel morphology and dissolved oxygen. Thresholds of biotic degradation can range from 3.6 – 15% imperviousness for fish and macroinvertebrate diversity and abundance, whereas abiotic thresholds such as water quality or habitat availability range from 4 – 50% imperviousness (Brabec, Schulte & Richards 2002). Considering many highly urban catchments have impervious areas between 30 and 95% (Allan 2004), there are clear benefits to be realised from the pursuit of this concept in remediating urban streams and mitigating future problems.

However, the biotic measurement may be more accurate in measuring stream health as biota generally reflect the long-term health of the stream rather than chemical changes that may be short-lived due to stream flow and immigration from surrounding unaffected areas (Brabec, Schulte & Richards 2002; Wheeler, Angermeier & Rosenberger 2005). Furthermore, aquatic communities appear to be more affected by habitat changes than water quality changes, and thus by a lower level of imperviousness than that which degrades water quality (Brabec, Schulte & Richards 2002).

In cold climates frozen ground and snow cover complicates the issue of imperviousness. Frozen ground can be viewed to some degree as an impervious surface (also referred to as 'concrete frost'), however there is generally only a short space of time before and after snow cover that frozen ground is available to contribute to runoff. Furthermore, soil water will be able to filter through large pores if the onset of freezing conditions is not closely following the last rainfall. This will mean the soil will have a greater ability to infiltrate the spring meltwater, and consequently less imperviousness (Muthanna *et al.* 2007). If soil water freezes in a granular way, infiltration can be maintained and even exceed the capacity of unfrozen soil (Muthanna *et al.* 2007), and this has important implications for the application of WSUD in cold climates, but is of course very site-specific.

1.3. Urbanisation and stormwater quantity

The impacts of urbanisation on stormwater quantity are well documented in the literature, as these studies were rooted in the desire to mitigate flooding to protect citizens and property in urban areas at the lowest cost to the state. The most obvious changes occur with increasing imperviousness and the removal of vegetation (Walsh *et al.* 2001; Brabec, Schulte & Richards 2002; Goonetilleke & Thomas 2003; Sansalone, Liu and Kim 2009; Yang *et al.* 2010). The removal of vegetation in the catchment reduces evapotranspiration, surface roughness and catchment storage ability, and the increase in impervious area results in reduced infiltration, depression storage and more uniform surface slopes in the catchment (Goonetilleke & Thomas 2003). These changes significantly alter the stream hydrology regime, increasing flow volumes and especially peak flows ('flashiness') and reducing catchment lag (ie. time to peak runoff). Some studies have shown up to 70% reduction in catchment lag in urban areas (Goonetilleke & Thomas 2003). Peak runoff can be 1.3 – 6 times larger in urban catchments (Goonetilleke & Thomas 2003).

This leads to channel morphology change such as scouring and bank erosion, which can be exacerbated by historical management efforts to increase hydraulic efficiency in urban areas through channelisation and straightening (Brown & Caraco 2001). The number of runoff events tends to increase relative to a rural catchment, with even low intensity rainfall events producing runoff (Goonetilleke & Thomas 2003). In Melbourne, Australia some previously ephemeral streams have become perennial and pre-development stream flow regimes of low summer flows and high winter flows have been evened out (Walsh *et al.* 2001; Goonetilleke & Thomas 2003), changing habitat conditions for biota.

The impact of imperviousness on stormwater quantity and the stream hydrology regime depends on the type, location and extent of impervious surface, and the layout of the stormwater network. Sections of urban areas located close to streams will lead to very rapid runoff of stormwater to the stream, but will not pick up as much pollutant load as urban areas located in the upper part of catchments, which will exert a more significant impact on stream hydrology due to increased slope (Goonetilleke & Thomas 2003). However research indicates that imperviousness is more significant for high frequency storm events (ie. less than 100 year Average Recurrence Interval) as larger storms usually carry such high intensity rainfall that the entire catchment can generally be considered impervious due to saturation of the catchment (Goonetilleke & Thomas 2003).

In the cold climate context, winter conditions will generally lead to a marked reduction in stormwater quantity due to snow cover. However, many cities employ snow management regimes that remove urban snow and transport it to local and regional dump sites, but in some cases dump it directly into urban streams (Engelhard *et al*. 2007), or the sea, as in the case of Helsinki, Finland (Ruth 2003). This can not only add a significant amount of water to a stream, it can also add a range of pollutants as well as altering stream temperature, which has significant effects on biota, and can cause 'shock stress' and acute toxicity (especially of salt) on certain fish species (Engelhard *et al*. 2007). In cold climates the spring flood is usually the most significant annual stormwater event, bringing large quantities of snowmelt through the stormwater network and into streams, along with a huge quantity and range of pollutants.

1.4. Stormwater quality – paths & processes

Urbanisation not only causes significant changes in stormwater quantity, but also generates a large amount and range of pollutants, from construction, transport, energy production and various industrial emissions. These are carried by rainfall from the air and land surface to stormwater pipes and subsequently to the nearest water body, fundamentally altering its natural characteristics and degrading habitat. Imperviousness leads to larger runoff flows and thus greater entrainment of pollutant particles from the land surface. If a particular storm event is preceded by a relatively long dry period, urban stormwater can be of lower quality than secondary treated sewage (Ritter *et al.* 2002; Goonetilleke *et al.* 2005).

The sources, pathways and fate of stormwater pollutants is a complex issue as it involves many media, as well as varying spatially and temporally. However there are generally several primary pollutant sources: street surfaces, industrial processes, construction, corrosion of materials, vegetation, litter, spills and erosion. Of these, pollutants gathered on street surfaces from vehicles, road decay and construction contribute the largest fraction.

Roads and highways constitute perhaps the single largest source of stormwater pollutants as they represent a large area of impervious surface and contain highly efficient stormwater pipe networks (see Figure 11, p.48). Materials present on street surfaces originate mainly from vehicles (lubrication losses such as crankcase oil and anti-freeze, exhaust emissions, load losses, degradation of brake linings and tires, corrosion of chassis and paint surface, and road surface wear) but also from atmospheric deposition (Ritter *et al.* 2002; Goonetilleke & Thomas 2003). Street dust and various sizes of particulates accumulate these materials and metals such as Pb, Cu, Cd, Cr and Zn, which are then washed-off following rain. The process of wash off is complicated and often site-specific, being highly correlated with weather and climate, traffic density & type, driving style, street sweeping frequency and type, and a range of similar factors, many of which are difficult to quantify (Goonetilleke & Thomas 2003). Street dust is often highly basic, resulting in an increase of the receiving water body's pH after rainfall (Brabec, Schulte & Richards 2002).

The highest concentrations of street pollutants are usually found in "hotspots" such as parking lots, intersections, taxi ranks, petrol stations and outside auto-repair shops (Schueler 2000a; 2000b). Furthermore, roads and highways themselves are often constructed using industrial and municipal waste products as base material, which helps to solve the disposal problem but leads to pollutant entrainment during the construction phase and during road wear and deterioration (Wheeler, Angermeier & Rosenberger 2005).

In cold climates such as in Scandinavia, Canada and the US, road salt (NaCl – Sodium Chloride) and sand is commonly applied as de-icing material, and consequently forms one of the largest single pollutant sources of stormwater and urban streams in those areas. Salt is highly water-soluble and so is easily entrained in stormwater runoff, especially in the spring flush of snowmelt (Ritter *et al.* 2002; Engelhard *et al.* 2007). The sand contributes to higher sediment load, increasing turbidity, and can also help adsorption of heavy metals. In lower quantities salt is also used as a dust-suppressant, and so may be present on street surfaces well into the spring (Ritter *et al.* 2002). The solubility of salt and its concentration in stormwater often reduces pH, leading to elevated adsorption of Cu and Pb (Ritter *et al.* 2002; Goonetilleke & Thomas 2003; Engelhard *et al.* 2007). In Helsinki, Finland, despite evidence that 30 – 50% of NaCl applied to roads & highways is discharged to waterways via stormwater drains (Ruth 2003), road salt has less of an effect on pH due to cation exchange between low pH rainfall as a result of transport and power generation emissions and very basic pH street dust (Ruth 2004). A study in Pennsylvania reported 20 – 30 times greater conductivity in a stream following winter thaw (Wheeler, Angermeier and Rosenberger 2005) and in Helsinki spring flood salt concentrations can be up to 1300 mg/L (Ruth 2003). In the Don River, Toronto, autumn concentrations of salt were reported to be 100 – 150 mg/L but rose to 1000 mg/L following the spring thaw (Ritter *et al.* 2002). Generally only pollution-tolerant macroinvertebrate communities and some tidal fish species can withstand such ‘shock’ salt loading.

Construction sites and demolitions also contribute a large fraction of suspended solids and sediment (up to 100 times higher than other land uses) to urban stormwater (Goonetilleke & Thomas 2003), however quantities depend on the size of the development, and specific management at the site such as erosion control measures. Sediment load can also come from material stockpiles of sand and cement at such sites.

1.4 Management with WSUD

Traditional stormwater management techniques have evolved from basic flood protection in the form of detention/retention basins, to more complicated Best Management Practices (BMPs) as considerations of poor stormwater quality and stream health became important. These involve a suite of measures often used in concert such as gross pollutant traps, swales (stone or grass-lined), wetlands and riparian buffer zones, among others (Goonetilleke & Thomas 2003). These BMPs may have varying effectiveness with consideration of local site conditions, design, maintenance, seasonality and climate (Brabec, Schulte & Richards 2002; Goonetilleke & Thomas 2003). BMPs are focused on treating stormwater to remove selected pollutants such as heavy metals, suspended solids and sediment before it reaches the receiving water body. There is therefore much less emphasis on safeguarding water quality in the holistic sense, but on treating the symptoms, rather than the problem itself. Some research suggests that BMPs cannot mitigate the effects of urbanisation once imperviousness reaches 20% in a given catchment (Brabec, Schulte & Richards 2002). These limitations are increasingly being recognised, and BMPs have rightly been criticised for being 'end of pipe' solutions (Goonetilleke *et al.* 2005; Dietz 2007; Roy *et al.* 2008).

A consequent evolution of stormwater management to treat the problem rather than the symptoms of stormwater quality is occurring, and seeks to incorporate more 'green design' aspects into new and existing urban developments, in combination with more traditional stormwater quality management techniques. This suite of techniques (often collectively called 'green infrastructure') can include porous pavements, green roofs, raingardens (interchangeable term with bioretention), roadside grassed swales, infiltration islands in parking lots and other key impervious areas, and sand and organic filters, among many others (US EPA 2010). There are also many different non-structural stormwater management techniques, such as stormwater inlet drain stenciling (Fig. 3), school and community education programs, street and drain cleaning, and education of "hotspot" businesses such as petrol stations and auto repair shops (US EPA 1999).

Figure 3. Stormwater drain stenciling: an example of non-structural BMP. Source: Washington State University.

Bioretention facilities have received the most research attention, and have also been tested for effectiveness in cold climates, whereas many other WSUD techniques have not. A bioretention facility, also called a raingarden, is a depression along which stormwater is directed, consisting of a sandy loam soil, a mulch layer and plants designed for uptake and infiltration of water (Muthanna, Viklander & Thorolfsson 2008). Hyper-accumulating plants can be chosen to maximise uptake of pollutants by plants (Muthanna *et al.* 2007). Bioretention is designed to reduce peak flow volume and improve water quality through infiltration and plant uptake (Muthanna *et al.* 2007a). Muthanna *et al.* (2007) tested the effectiveness of bioretention to treat snowmelt from roads in Trondheim, Norway, and reported a mass reduction of 89-99% for Zn, Cu, Pb and Cd, and found that the top mulch layer accumulated the most metals, while plant metal uptake was only 2 – 8% of the total. Many studies have found similar results for metal removal (Weiss, Hondzo & Semmens 2006; Muthanna *et al.* 2007a; Li & Davis 2009). Despite that the plants used in bioretention are not usually the major source of pollutant removal, they are still important in root zone development and regeneration, which enhances infiltration and reduces outflow. They are also important aesthetically and are valuable for wildlife.

There is some doubt over the efficiency of bioretention and WSUD in general to perform effectively in cold climates, mostly in relation to money spent on techniques that work in warmer climates but not in colder ones. There is contradictory evidence in the literature to this effect, with some studies indicating good performance during winter for heavy metals (Heyvaert, Reuter & Goldman 2006; Dietz 2007; Muthanna *et al.* 2007; Roseen *et al.* 2009) phosphorus and suspended solids (Blecken *et al.* 2010), but indicating impaired peak flow reduction and winter removal of nutrients, suspended solids and hydrocarbons (Dietz 2007; Muthanna, Viklander & Thorolfsson 2008; Blecken *et al.* 2010). Among the suggested reasons for the discrepancies are species used, time taken for maturation of plants, and reduced microbial activity due to cold temperatures (Werker *et al.* 2002).

Concerns about frozen soil and other media creating blockages in bioretention systems leading to system failure and maximized flooding could be misguided, considering the overall picture in cold climate studies. One study from Connecticut with measurable frost reported 99% of inflow being infiltrated or evapotranspired over a two year period and another finding that rapid thawing of soil occurs on contact with stormwater runoff (Dietz 2007). Although all WSUD stormwater treatments must be designed with local conditions in mind, their application to cold climate conditions should be supported, with some adjustments for lower temperatures (Blecken *et al.* 2010). While this paper is not by any means an exhaustive review of the application of bioretention in cold climates, it serves as an indication of future possibilities.

Future areas of research would include further studies on bioretention in urban areas in cold climates, to elucidate the ways in which winter conditions affect uptake of nutrients such as nitrogen and phosphorus, as well as hydrocarbons and dissolved organic carbon. The conditions of rain-on-snow events and mid-winter thaw events as seen in some northern coastal cities such as Trondheim, Norway create unique challenges for researchers attempting to integrate WSUD techniques in stormwater management, and greater attention is needed in this area. More research is also needed on the effectiveness of other WSUD techniques in both warm and cold climates, and plant species composition and density for different techniques.

Water Sensitive Urban Design can be seen as one step in a holistic treatment train for stormwater. Not only does it hold promise for reducing the problem of pollutants of stormwater rather than the symptoms, it is often aesthetically pleasing, design oriented and can provide quality and compensatory habitat for native species. It can be used to systematically redesign cities to be much more water efficient and effective in reducing the generation of pollutants. Combined with research on impervious area of larger catchments, and continued societal change, these treatments have the potential to effect real quality enhancement of urban stormwater and urban streams. Although it must be accepted that urban streams in areas with greater than about 25% imperviousness can likely never be returned to their complete natural state, they can still be maximised for ecological and recreational value with reasonable water quality (Schueler 1994). Moreover, if EIA is used as the primary indicator of urban stream health, then it may be possible to 'stretch' the imperviousness-stream health ratio to allow for higher density and more compact cities.

The vision to strive for is of a functional city with a high TIA of up to or even greater than 50%, but with an EIA of less than 20%, which, according to Schueler's (1994) rankings of stream health, would bring urban streams down from "non-supporting", to "impacted", allowing greater opportunity for ecological restoration and recreational value. In this city most of the buildings and transport infrastructure would not be connected to the stormwater system directly, but the water would be reused in many different ways (in gardens, toilets, water-using appliances etc.), in addition to infiltrating into the soil, with the remainder to be led through a series of different BMPs before reaching the stream. Only the buildings and roads in the most impervious areas of the city (for example the Central Business District) where there is very little space for BMPs would be connected to the traditional stormwater system, and even here there are myriad opportunities for reuse through green infrastructure.

What is clear is that the cities cannot afford, environmentally and monetarily, to continue to build roads and buildings with traditional sprawl patterns and its associated stormwater infrastructure. This should be the aim when assessing the suitability of green housing developments, and the KUNTA project is a trial of that idea for the City of Helsinki.

Within this framework, this paper provides an assessment of current water quality in the stream, and gives indications of what the water quality is likely to be following build-out. Moreover, a central aim is to promote imperviousness as an indispensible indicator to aid water-friendly urban planning, through its relation to water quality, and as a tool to develop sustainable preventative planning and promote the applications of WSUD. Accordingly, it is critical to obtain as accurate a measurement of Effective Impervious Area (EIA) as possible in order to size stormwater BMPs accordingly and minimise costs.

Finally, this paper briefly assesses the stormwater management practices planned for the KUNTA development, discussing how new urban areas can be developed with sustainable water management principles in mind, and how existing practices can be strengthened and promoted, with emphasis on the techniques that are effective in cold climate conditions. The advantages of a watershed-based zoning method will also be covered, to aid planners in recognising and prioritising different categories of streams with specific management options, and to advance the use of preventative planning to minimise hydrological disturbance and reduce costly flooding issues.

This project can therefore be seen as a monitoring case study of the larger concept of imperviousness and its effect on water quality and quantity, and the importance of integrating sustainable water management with urban planning. In this way it is hoped that this paper will give some projections as to how the catchment and stream will react following development, and how water quality & quantity issues can be mitigated with sustainable planning.

2. Materials and methods

2.1. Research area

The research area (Fig. 4) of this study was chosen due to the planned development that will take place in the upper catchment of Hakuninmaanoja. This stream is a tributary of Mätäjoki, the second largest river by discharge in the Helsinki region, as well as a significant recreational resource for the city. The catchment of Hakuninmaanoja is located in the north part of the City of Helsinki just south of the municipal border with Vantaa along the Vantaa River (Figs. 4, 5, 6). The area of the catchment is 134 hectares, and is primarily a single-family house residential area, retaining approximately 72% forest cover, a figure that is typical of Finnish suburbs. Asphalt transport areas form the next largest category of land cover (12.2% of catchment area), followed by close and very close small houses (4%), indicating the suburban character of the catchment (Table. 1).

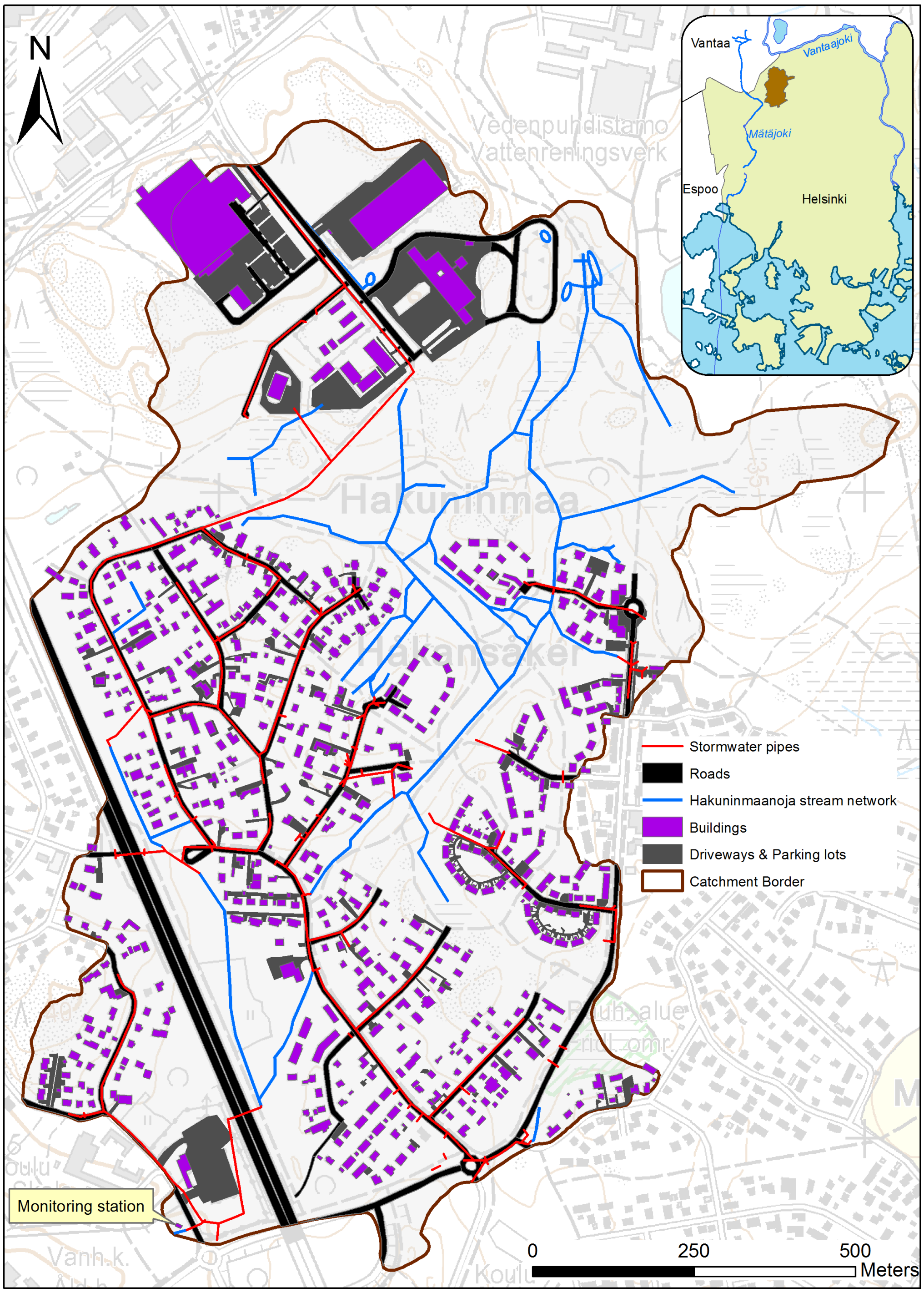


Figure 4. Location of Hakuninmaanoja catchment within Helsinki region & detail within catchment. (Peruskartta [Basic map] 1:20,000, UL4134L, UL4133L, UL4132R, 2010).

Table 1. Percentage of various land uses in Hakuninmaanoja catchment, using Kuusisto's (2002) Finnish land use categories.

Land cover category	Percentage of catchment area (%)
Close small houses	3.48
Very close small houses	0.66
Rowhouses	1.74
Industrial	2.42
Forest	72.41
Transport areas: gravel	1.41
Lawn	4.63
Transport areas: asphalt	12.29
Water	0.96
Total	**100**

The northern part of the catchment is the location of the headwaters of Hakuninmaanoja, and also a small area of industrial land use, comprising a printing factory, and several other factories and warehouses. Outside the catchment to the northeast is a water treatment plant, and its former settlement pond. The whole industrial area and some forest areas to the northeast and southwest, as well as the former settling pond, will comprise the new Kuninkaantammi development (Fig. 5).

Figure 5. KUNTA development plan, phase one in colour. Source: Suvi Tyynilä (2011).

The stream network itself has been modified over time; firstly before the 1930s when the area was agricultural, drainage channels were cut across the land and have artificially connected some tributaries, especially in the upper catchment (see Fig. 4). As the urban area in the catchment has been built, some of these channels have been become part of the stormwater drainage from particular areas of houses, and other parts of the stream network have been straightened and integrated into the roadside drainage network or put underground.

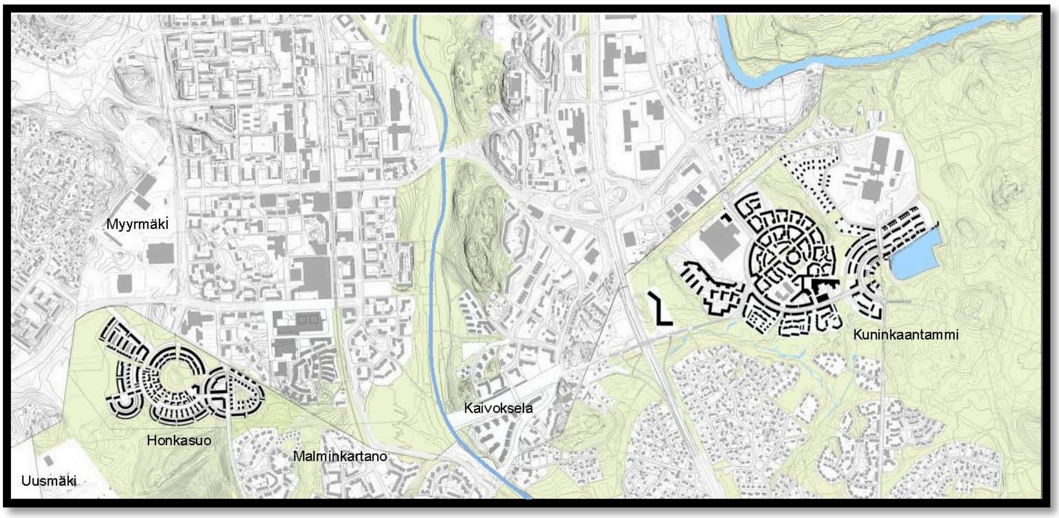


Figure 6. Location of KUNTA development in northern Helsinki area. Source: Suvi Tyynilä (2011).

As part of the general environmental impact assessment for the KUNTA development, the City of Helsinki provided funds for the construction of an automatic monitoring station, located on the lower end of Hakuninmaanoja, approximately 200m above its confluence with Mätäjoki. For ease of calculations, this point was used as the outlet of the catchment when determining the size of the catchment in ArcGIS.

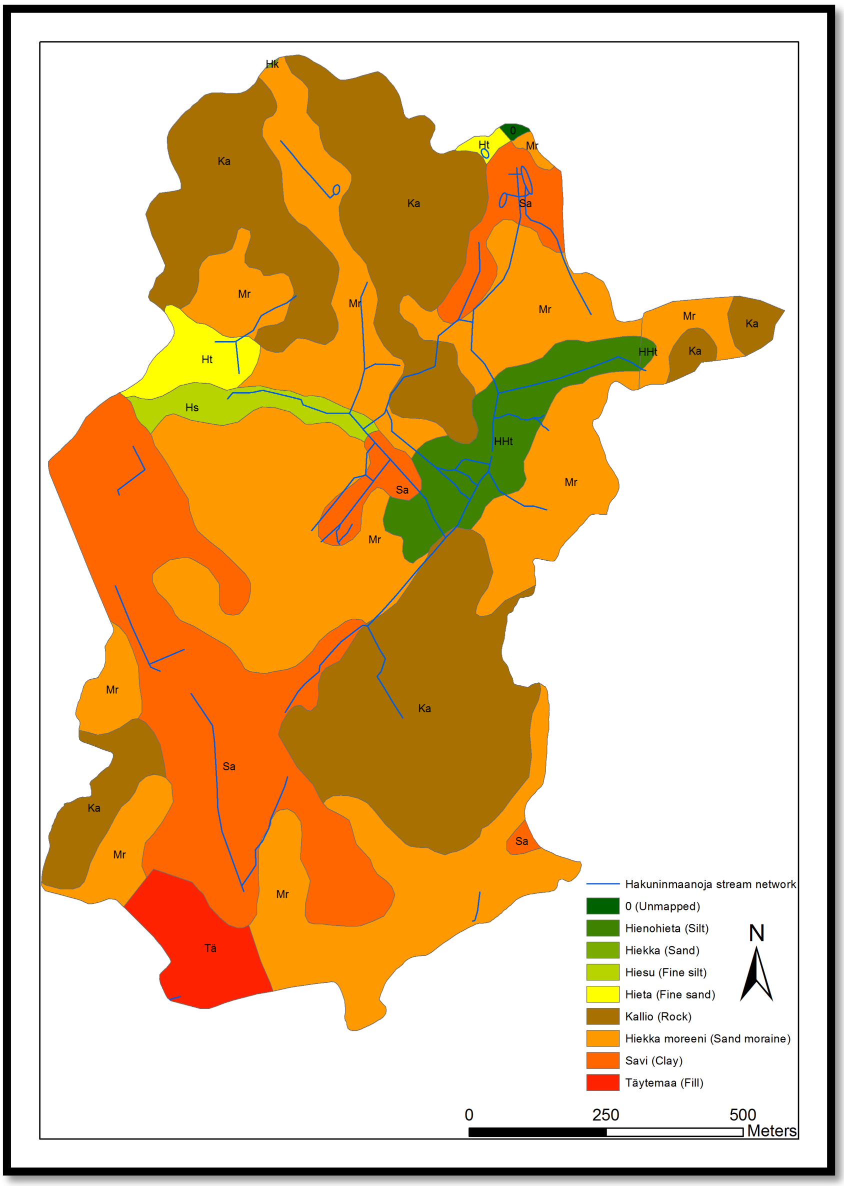


Figure 7. Soil map of Hakuninmaanoja catchment. (Geological Survey of Finland. 2012. 1:20,000, data from 1972-2007. Sheets: m204304, m204301).

The soils are mostly characterised by sand moraine, rock, and clay, in descending order (Fig. 7; Table 2), which is typical of Finnish conditions. Areas of low infiltration capacity comprise over 50% of the catchment. Note however that rock areas include not only exposed bedrock, but also areas where bedrock is overlaid by soil to a depth not greater than one metre. The rock area is significant because it can be considered also as an impervious surface (Arnold & Gibbons 1996), though is rarely (due to difficulty) included in calculations as such.

Table 2. Soil types in the catchment. (Geological Survey of Finland. 2012. 1:20,000, data from 1972-2007. Sheets: m204304, m204301).

Finnish	English	% of catchment
Karttoittamaton	Unmapped	0.08
Hienohieta	Silt	4.73
Hiekka	Sand	0.01
Hiesu	Fine silt	1.65
Hieta	Fine sand	1.79
Kallio	Rock	30.29
Hiekka moreeni	Sand moraine	38.57
Savi	Clay	20.11
Täytemaa	Fill	2.79
Yhteensä	**Total**	**100**

2.2. Water quality monitoring & sampling

Water quality in Hakuninmaanoja was monitored over a five-month period, from 29th June to 25th November 2011. However, continuous data (readings every 30 minutes) was obtained only from 29th June to 19th September, due to a human error in data management which meant that data from 20th September until 15th November was accidentally overwritten. After 19th September only hand sampling took place.

2.2.1. Automatic monitoring

The terms of the agreement with the City of Helsinki over the KUNTA project allocated funds for an automatic monitoring station to be built with a weir on Hakuninmaanoja, with a view to operate it for at least 5-10 years. The idea was to monitor the water quality prior to the KUNTA development, during the construction phase, and after the development is finished. However due to the much shorter timescale of a Master's thesis, this project would have use of the facility for only a fraction of that time. The Dept. of Geography & Geosciences at the University of Helsinki received funds from the City of Helsinki to buy the water quality monitoring equipment, while the actual construction of the weir and the temporary office building was overseen by the City of Helsinki. Unfortunately

Figure 8. YSI probe after being moved by storm water, July 2011. (All photographs taken by the researcher unless otherwise indicated).

there was a long delay in the construction of the station (construction was expected in March 2011 but was actually finished in September), and as a result it was decided to place the water quality monitoring probe in the stream without waiting longer for the weir and facility to be built. The probe that was used was an YSI Sonde model 6920 multiprobe (YSI Inc., Yellow Springs, OH, USA) measuring eight parameters (Temperature, Electrical Conductivity, Depth, pH, Oxidation Reduction Potential, Nitrate, Turbidity, and Dissolved Oxygen) every thirty minutes. A small weir was built by hand with rocks to increase the water depth enough for sampling to occur. However, the fact that the probe was lying on the bed of the stream and not fixed in place meant that it was sometimes thrown clear of the water by storms (Fig. 8), and in dry periods over the summer of 2011 the water was occasionally too low to be sampled. This data was removed from the analysis due to being unreliable. The probe was in this state for three months before the weir and station was built, and due to this the project was unable to determine discharge during that time, a critical parameter to understand the effect of impervious surfaces on hydrology. As discharge data was not available, it was decided to correlate water quality parameters with rainfall data only. Although a rainfall gauge was installed at the monitoring facility in September, this was at the end of the available automatic water quality monitoring data, therefore only rainfall data from Helsinki-Vantaa airport was used for the entire water quality dataset applicable to this thesis.

The weir and station were built at the end of August 2011 and the probe was moved to a safer position within the weir. During the 26 Aug- 1st Sep period, the probe was continually being moved by workers, out of water or covered in construction sediment, and therefore these dates were removed from the dataset.

Figure 9. ISCO Model 6712FR Automated Water Sampler & Refrigerator used at KUNTA monitoring station. September 2011.

An ISCO Model 6712FR Automatic Water Sampler and Refrigerator (Fig. 9) was purchased for the project and installed at the site by Elliot Stuart and his supervisor Olli Ruth. This was extra work related to the KUNTA project but outside the actual thesis work, and involved laying intake and heating cables from the weir to the office, connecting and programming probes and settings, and installing software to the computer. The system was set up with a GSM mobile connection, allowing a text message to be sent to the ISCO sampler at any time that instructed the machine to take water

Figure 10. Hakuninmaanoja, looking downstream, before (left) and after (right) weir construction. August 2011.

samples, allowing samples to be taken as close to the start of rain events as possible, without actually being at the site. However, teething problems with the programming of the ISCO system meant that on several occasions the sampler filled too many bottles or put too much water in each bottle, contaminating the previous samples.

2.2.2. Sampling & laboratory analysis

Hand sampling using one-litre bottles was carried out from 4th July to 25th November 2011, resulting in seventeen regular samples and three samples that were taken in acid-washed bottles for metal analysis. However, this was considered to be too small a sample set to be representative of the real world water quality, hence the metals analysis will only be referred to briefly, although the data can be found in the appendix. Two bottles were taken each time as a backup in case one was contaminated. The analysis was performed by staff at the laboratory of the Dept. of Geography & Geosciences at the Kumpula Campus of the University of Helsinki. This was due to time constraints and university regulations concerning student use of the laboratory facilities. Analysis comprised:

Suspended Solids (mg/L)
Loss on ignition (%)
Organic solids (mg/L)
Dissolved solids (mg/L)
Total Nitrogen (mg/L)
Total Phosphorus (mg/L)
Sodium (mg/L)
Potassium (mg/L)
Calcium (mg/L)
Magnesium (mg/L)
Fluoride (mg/L)
Chlorine (mg/L)
Nitrate (mg/L)
Phosphate (mg/L)
Sulphate (mg/L)

Metal analysis included Copper (ppb), Zinc (ppb) and Nickel (ppb). Phosphate analysis unfortunately could not be relied upon and appears in appendix only.

2.3. Determination of catchment imperviousness

Impervious area can be determined in a number of ways, with varying accuracy and cost. Generally, the most accurate method is also the most expensive. Over large catchments or whole cities, satellite imagery or a combination of those with aerial or helicopter photographs are the most practical. Empirical equations have also been used with varying success to determine EIA from TIA (eg. Alley & Veenhuis 1983, Sutherland 1995). Over smaller areas, such as catchments less than 200ha in size, field surveying is more appropriate, and can result in highly accurate determinations of impervious area, and especially the fraction which is directly connected to the stormwater system (EIA). It is much more difficult to determine EIA using aerial photographs, due to cloud cover, tree canopy, and shadowed surfaces, though there are constant advances being made in this area, for example through high resolution satellite imagery from the IKONOS satellite (Cablk & Minor 2003; Han & Burian 2009). As rooftop and downpipe connectivity (the key to calculating EIA) cannot usually be determined with remote sensing (Lee & Heaney 2003; Roy & Shuster 2009), field surveying is currently the most accurate method of determining EIA, and due to the small catchment size (134ha), it was undertaken in this study. Field surveying impervious area involves extensive ground-truthing and labeling of catchment features that can often only be discovered during a physical site visit, such as rooftop connectivity and gutter pathways. However, in order to demonstrate the accuracy of the field survey method, imperviousness was calculated using a second method, known as the Land Use Category (LUC) method. This is less time consuming (and therefore less expensive) but less accurate technique, which uses land use categories and runoff coefficients based on slopes and soil types from Finnish conditions (see Table. 3, p.39, Kuusisto 2002). This process gives area-weighted runoff coefficients for each land use based on soil and slope. Runoff coefficient is defined here as the fraction of rainfall which is converted to runoff from a given land use. This is a slightly different approach to dealing with catchment imperviousness (Fig. 11), however they can be considered similar except at low levels of imperviousness where soils and slope become more important (Schueler 1994). Increasing imperviousness increases the amount of rainfall that will become runoff.

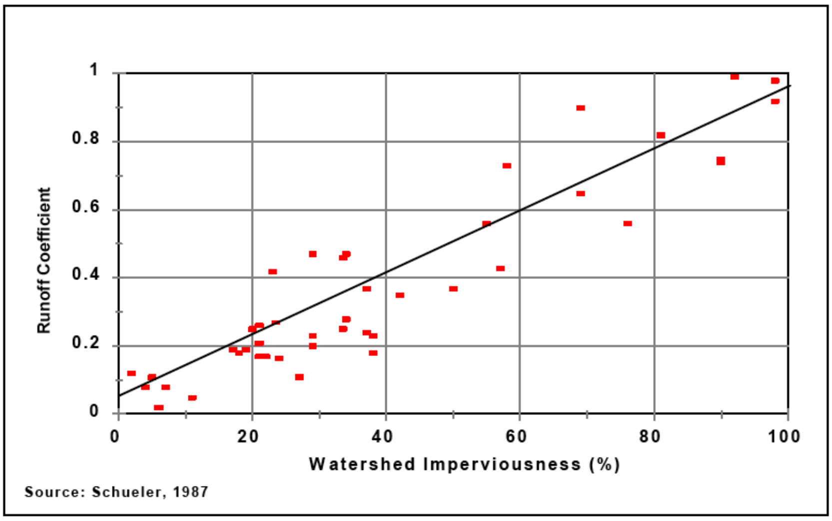


Figure 11. Relationship between runoff coefficient and catchment imperviousness. Source: Schueler (1987), in US EPA (1999).

The LUC method involves dividing a catchment into various land uses applicable to local conditions, soil types and slope angles, and the intersection of all three is given a unique runoff coefficient between 0 and 1. Zero means that no runoff will be generated during a rainstorm, and one means that 100% of the rainfall will become runoff from that particular land use. Each category of urban features will thus have nine different runoff coefficients. This means that even land uses such as forest have some degree of imperviousness, or in other words, will generate a varying degree of runoff depending on the underlying soil and slope. The steepest slopes (>4°) and soils of clay, silt, mud or rock will generate the most runoff from their land uses (due to gradient and low infiltration capacity), which will be compounded by the different urban features on top. This study translated into English and adapted the Land Use Categories developed by Paula Kuusisto (2002) for Finnish conditions.

Finally, the results of the two techniques were compared to demonstrate the accuracy of the field survey technique, and its relevance to practical applications in urban watershed planning of small catchments. The resulting maps produced using ArcGIS software have enabled a very detailed picture of the current and future characteristics of the catchment to emerge.

2.4. Guide to field surveying Effective Impervious Area

The purpose of this section is to provide a simple guide for students and researchers wishing to undertake a field survey of catchment impervious area. While the literature is replete with references to field surveying, there is actually very little practical information on how to do it, and what materials are needed before beginning. Two useful articles are Lee & Heaney (2003) and Roy & Schuster (2009). However, it would have been a great help to this research if there had been more detailed information to guide this process, and as a result some mistakes were made which could not be resolved.

The maps used in field surveying impervious area should include land parcels, topography and other physical features, both urban (pavements, paths, buildings, outbuildings, parking lots etc.) and natural (stream network, ponds & lakes) and have a scale large enough to see all the features of the properties, including the corners of the buildings (where downspouts are usually located), their position in relation to each other and to the roads and stormwater system, and if there are gutters leading water over the surface to lawns or to roads and therefore stormwater infrastructure (Fig. 12).

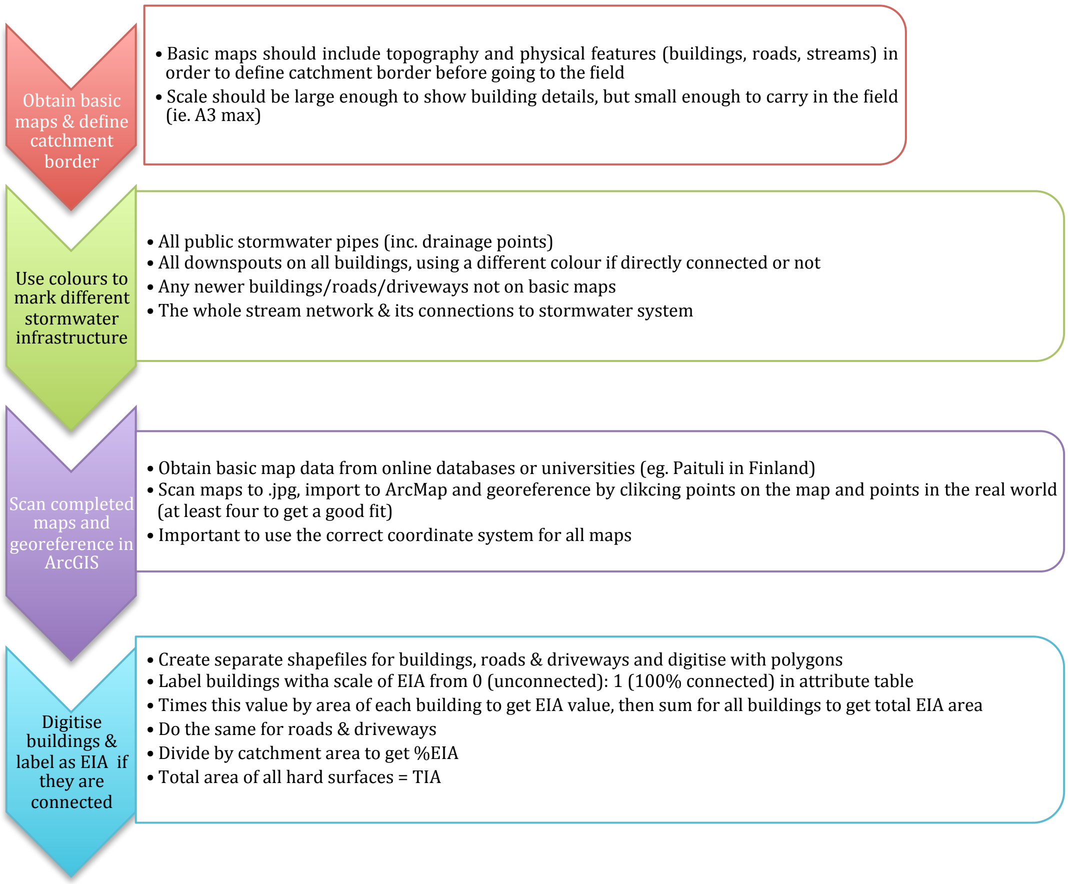


Figure 12. Flow chart illustrating the field survey process.

The labeling system (Fig. 13) should include coloured points representing the downspouts coming from each roof, with purple indicating non-connectivity with stormwater pipes and yellow indicating connectivity (see Figs. 13 & 14 for examples of connected and non-connected roof downspouts). Stormwater infrastructure (Fig. 13, in red) should be drawn on each map before the fieldwork has begun. This way it is easier to see the connection between individual houses and roads with stormwater pipes. New buildings, and some driveways were hand-drawn in this field survey, as the map that was used was not completely up to date.

Driveways were coloured black for asphalt and brown for gravel, and brick driveways were labeled as such, because that material has a slightly lower runoff coefficient than asphalt. Some old buildings did not exist anymore and were removed or drawn over with the newer building. The circle with a cross inside represents drain intakes.

It is important to include as much information as practical in the field survey: it is better to have the option to use it rather than to not have the information at all. For example, even though the information was collected during the field survey, it was deemed to be too much work to digitise every gravel driveway, especially considering they would not have much influence on total imperviousness, and so only those which were connected with drains to the stormwater infrastructure were digitised. Similarly, it was decided to be too much work to differentiate precisely between different greenspace types, such as garden, lawn, park, grassland and forest, although these were roughly grouped during the ArcGIS analysis and incorporated into the Land Use Categories determination of catchment impervious.

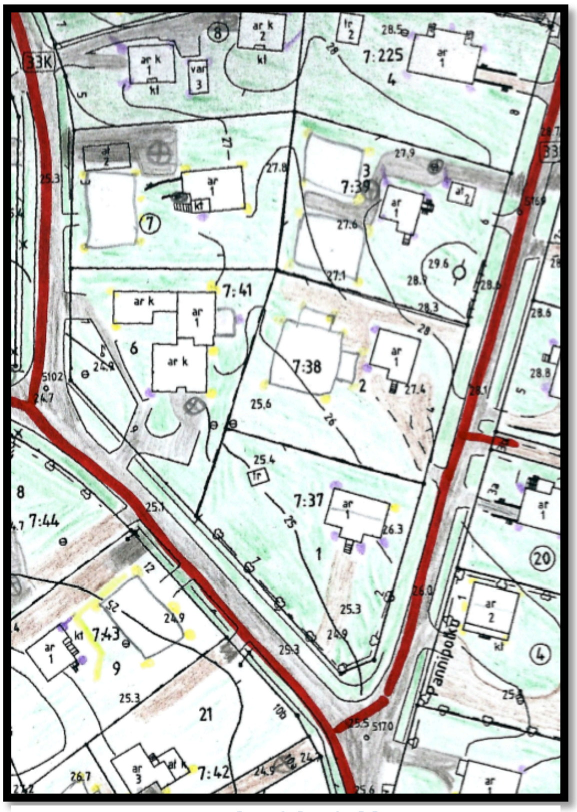


Figure 13. An example of the field survey maps and labeling system used in this project. Base map of the City of Helsinki, scale 1:500, max error 5-25cm. Map source: City of Helsinki (2005).

Figure 14. Example of non-connected rooftop (left, with rainbarrel), and connected rooftop (right picture) found in Hakuninmaanoja catchment during field survey. September 2011.

Challenges associated with Field Surveying

Even with the right preparation, problems will be discovered during the course of the field survey, some of which are difficult to resolve. Occasionally, a roof can seem disconnected, but there may be gutters or depressions set into the driveway, which leads the water to a drainage inlet into the stormwater system. This requires simply a closer look at where the water goes after leaving the roof. Conversely, in other places a building can seem connected, with pipes linking the roof to underground infrastructure, and this requires a longer search around the property or adjacent properties for a drainage ditch where the rooftop runoff is being led (Fig. 15). This means that the building in question is not EIA as the water ends up in a ditch where it will infiltrate rather than enter the public stormwater system.

Figure 15. Two photos from the field survey illustrating the difficulty of determining EIA. To the left the downpipe looks as if it is connected to underground pipes, but 10m away the pipe comes out into a ditch (right photo). Two other houses adjacent to this property also had pipes which led rooftop runoff to this ditch. These houses were not classified as EIA. October 2011.

The above photos are only one example of where this kind of system was discovered – it is not out of the question that other examples remained undiscovered and may have mistakenly included in the figures as EIA.

Another example of this kind of 'hidden' stormwater system arose during the field survey, where it was noticed that some properties have a system called "imeytyskenttä" in Finnish, which refers to an on-site underground infiltration system. With this kind of system, a building would look as if it is connected to the public stormwater system, however the pipes would lead only to this onsite infiltration tank. The water is led from the roof, and in some cases also the greywater, where it infiltrates through various layers of sand and gravel in order to remove pollutants. From there the water will travel naturally into either the shallow groundwater or to the nearest water body.

It is very difficult to determine whether a particular building has this kind of system, as there are usually no obvious physical signs above ground. The way that it was discovered in this project's field survey was through a chance meeting with the owners of two buildings with the system. Later, contact was made with the City of Helsinki to discover all the properties in the catchment with this system,

however there were no public records of these systems lodged with the municipality. In order to get this kind of information, the blueprint of each suspected property would need to be applied for and obtained, a time-consuming task. It is important for the prospective field surveyor to be aware of these issues and attempt to rectify them before surveying begins.
Unfortunately these issues were not anticipated in this field survey, and thus one of the aims of this guide is to prepare future students and researchers for these eventualities, and provide ideas for solutions. For example, another way to discover these kinds of stormwater runoff systems would be to speak to the owners of every building with a list of prepared questions aimed at discovering exactly what kind of system exists at each site. A drawback of this however, apart from being time consuming, is that many homeowners and renters do not know where their rooftop runoff goes. Moreover, there may be a language barrier between the researcher and some residents, as occurred during this field survey, making it difficult to ascertain whether any special stormwater systems existed at those properties (although hand signals and broken Finnish/English did work to some extent). This means that there can probably never be complete information on the characteristics of the buildings in the catchment.

The weather of the location at the time of field surveying is also an important consideration. In Scandinavia and other northern climates, it is obviously impossible to complete field surveying during the winter. However, during high summer it is also difficult as the height and density of vegetation, particularly adjacent to watercourses and in places where no maintenance occurs, makes access to and visual observation of stormwater inlets, drains and pipes problematic. Thus the best time to do this kind of surveying is immediately after the spring thaw or mid-late autumn, when vegetation is low and rainstorms can make it easier to see where water travels in places where it is otherwise difficult to determine, for example at the boundaries of the catchment.

Determining the boundaries of the catchment can also be problematic. The traditional geographic way to do this is by drawing a line that follows the high points on the map. In places where the high points of a catchment are merely bumps or low & flat hills, it can be difficult to determine exactly where the catchment border is, even when the researcher is physically on the spot. The built-up urban features of the landscape compound this problem by altering and interrupting the way water naturally travels in a catchment. As mentioned earlier, a rainstorm can sometimes help to see where the water travels, and thus to work out where the catchment border lies. This is complicated even further if a house, driveway, road or parking lot is built across the catchment border. In this case, very careful attention must be paid to the field maps and the locations of each roof downspout, the direction the water travels, and the locations of the stormwater pipes and inlets. It is very much possible to have buildings which are partly inside and partly outside a particular catchment, by having rooftop connections into two or more catchments. In higher density catchments this will have an effect on the TIA/EIA percentages.

It is important to liaise with municipalities responsible for urban planning, as local ordinances, by-laws and planning policies may affect the stormwater collection system. For example, the research area of this project is a low-density suburban area, where many older houses are not connected to the stormwater system. However, according to local residents, a new policy of the City of Helsinki states that all houses in the area must connect their buildings to the stormwater system within a year (as of September 2011). This will drastically change the TIA/EIA fractions, as all buildings will eventually become EIA. During the field survey some residents were already in the process of connecting their buildings to the underground stormwater collection system. This policy is something that will be argued against later in the paper.

Lastly, persons wishing to undertake field survey must be acutely aware of their legal and ethical responsibilities when on private property. University students will usually have permission to be on private property, however this should be discussed with superiors at each institution supporting the research, and a letter of permission should be carried at all times in the field, along with phone numbers of the authorising personnel.

The personal security of the researcher should also be considered prior to undertaking fieldwork, as dangerous animals and aggressive/unstable/suspicious residents are very much a reality. Care should be taken to be as clear as possible when talking to residents about the reasons why the researcher is walking around a property looking at the roof and the downspouts! In the case that permission to access a particular property is denied by a resident (as is their full legal right), it can help to access aerial photographs from Google Earth®, ground level photographs from Google Street View® and helicopter photographs if available (for example Finland's ENIRO database, providing 360° photographs from different angles and at low elevations in the Helsinki area).

2.5. GIS work and analysis

2.5.1. Field survey method

The field survey took approximately two months to complete over a catchment area of 134 hectares, containing 448 residential buildings and 1,906 residents. Population data was obtained from Finland's national PAITULI database.
The completed maps were scanned into .jpg format, and imported into ArcMap 10 software. A basic map of the catchment region, central Helsinki and western Helsinki, Espoo & Kauniainen was accessed from the Maanmittauslaitos - National Land Survey of Finland (2010, Peruskartta-Basic map 1:20,000, sheets UL4134L, UL4133L, UL4132R) using the PAITULI database. The field survey .jpg files were georeferenced using this basic map. This process turns the picture files into .tiff files which are then spatially referenced in the real world using the EUREF FIN spatial reference system.

As the scanned maps were A4 size, and the catchment is not a square shape, some overlapped others. In ArcMap there is a 'masking' feature which allows the overlapping sections to be cut out of certain map layers, and this was used to create a jigsaw pattern of scanned maps where none overlapped any of the others. From the PAITULI database, a building shapefile layer was added with polygons for most buildings in the catchment. As this layer was several years old, it was necessary to manually digitise the new buildings into this layer by drawing polygons over the scanned maps where they had been physically drawn in during the field survey. For the roads there was no pre-existing shapefile with roads as polygons, so one was created and all roads, asphalt driveways and gravel driveways which were connected to the stormwater system were digitised into it. For each shapefile, several fields were added in the attribute table: 'area', 'EIA value' (0 for unconnected, to 1 for completely connected, and a fraction between 0 and 1 for partially connected features), and 'EIA area'.

The EIA value for partially connected features was determined as follows: if a building had for example, three out of four downspouts connected to the stormwater system, it was given an EIA value of 0.75, meaning that approximately 75% of the water coming from the roof will enter the stormwater system and is therefore EIA. Different values were given depending on the situation of each building (see Roy & Shuster 2009 for similar methods).

Gravel and brick surfaces (eg. roads, driveways and parking lots) that had stormwater inlet drains within them were subject to a special process. Gravel was said to be approximately 80% impervious (in contrast to asphalt which is close to 100%), and thus the material was given a value of 0.8. This was multiplied by the area of that feature and included in the TIA total. For example a gravel driveway of area $500m^2$ would be included in TIA totals as $0.8*500 = 400m^2$. Therefore surface materials are already taken into account in the TIA totals. If the feature was connected or not it was given the appropriate EIA value of 1 or 0, which was then multiplied by the TIA (m^2) to give EIA (m^2). If that same gravel driveway was unconnected then it would not be included in EIA totals. Transport infrastructure was always given either 0 or 1 (connected or unconnected) and never a value between because it was determined to be too much work to calculate what percentage of the surface would drain to grass, garden or forest on either side due to slope, age of surface, intensity & duration of rainfall etc.

For buildings which were not connected directly to the underground stormwater system, but where the drainpipes and gutter systems led the water over asphalt (for example on a driveway or directly to the street gutters) to an inlet grate, that building was given an EIA value of 0.9. In this situation even though the building is not connected directly, approximately 90% of the rooftop runoff is expected to enter the stormwater system through those channels. If the water would run over gravel (for example a driveway) to an inlet grate, that building was given an EIA value of 0.7.

The formulas used to calculate TIA and EIA are as follows:

$$\% \, TIA = \frac{A_{build} + A_{drive} + A_{road}}{A_{catch}} \tag{1}$$

In this equation (1), A_{build} is the sum area (m^2) of all buildings, A_{drive} is the sum area of all driveways and parking lots (m^2), A_{road} is the sum area of all roads (m^2) and A_{catch} is the total catchment area (m^2).

$$\% \, EIA = \frac{[(x_{build})EIA_x + (x_{drive})EIA_x + (x_{road})EIA_x]}{A_{catch}} \tag{2}$$

In equation (2), x_{build} represents each building's area, which is multiplied by the EIA value for that building, given by EIA_x. All of these areas were then summed to give the total EIA area for buildings. Similarly, x_{drive} is the area of each driveway or parking lot, and x_{road} is the area of each segment of road, which again were both multiplied by their particular EIA value. The results of this process were then summed to give the total EIA areas for each of those features, which were added together and divided by the catchment area (A_{catch}) to give % EIA.

This process is illustrated below:

Building	**Area (m^2) (= TIA)**	**EIA value (0-1)**	**EIA area (m^2)**
1	4232.5	1.0	4232.5
2	95	0.5	47.5

2.5.2. Land use categories method

Using this method as a comparison helps to demonstrate the accuracy of the field survey method. The seven land use categories, three soil categories and three slope categories used in this project were adapted from Paula Kuusisto's (2002) determination of land uses appropriate for Finnish circumstances (Table. 3). This method is much faster than the Field Survey method, taking about one full workday with the correct preparation, but at a coarser resolution and a cost of accuracy.

Firstly, ArcMap was used with the basic map from the National Land Survey of Finland, and several layers of polygons in shapefiles covering all the categories that were determined to exist in the catchment (Table. 3, in yellow), the soil types and the slope types.

Table 3. Land use categories and runoff coefficients adapted and translated into English from Paula Kuusisto (2002). Only the categories highlighted in yellow were actually used in this project.

Slope/Gradient	**0-1°**			**1-4°**			**>4°**		
Soil category	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Scattered small houses	0.05	0.1	0.15	0.1	0.15	0.2	0.15	0.2	0.25
Close small houses	0.1	0.15	0.2	0.15	0.2	0.25	0.2	0.25	0.3
Very close small houses	0.15	0.2	0.25	0.2	0.25	0.3	0.25	0.3	0.35
Row houses/small block houses/well-spaced block houses	0.2	0.3	0.4	0.3	0.4	0.5	0.4	0.5	0.6
Close block houses, industrial & transport areas, schools	0.3	0.4	0.5	0.4	0.5	0.6	0.5	0.6	0.7
Very close block houses	0.4	0.55	0.7	0.5	0.65	0.8	0.6	0.75	0.9
Park	0.05	0.1	0.13	0.15	0.2	0.25	0.2	0.3	0.35

Forest	0.01	0.05	0.1	0.05	0.1	0.2	0.1	0.2	0.25
Transport areas - asphalt	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9
Transport areas - gravel	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
Field, meadow, lawn	0.05	0.1	0.15	0.15	0.25	0.35	0.3	0.4	0.5
Gravel fields	0.1	0.2	0.3	0.2	0.3	0.4	0.3	0.4	0.5
Water	1	1	1	1	1	1	1	1	1

A= Gravel, sand, peat

B= Moraine

C= Clay, silt, mud, rock

All the features within each category were selected with polygons according to their perceived best fit. For example, it is relatively easy to judge what category a particular building will fall into based on its shape on the basic map and its location relative to other buildings. Lawns were categorised and quantified by using a two-metre buffer around buildings, except where they overlapped other features. This was felt to be a fair approximation of the extent of lawns within the catchment, as generally lawns are not an extensive feature of Finnish gardens, at least compared with countries in warmer climates. Forests were determined to be the area outside of all the other categories, and this is very much the case in Finnish suburbs.

The nine soil types existing in the catchment were reclassified into the three soil categories from Table. 3, for example the soil type “fill” was determined to fit in soil category “A”.

A Digital Elevation Model (DEM) for the catchment was obtained from the PAITULI database, and reclassified into the three slope categories listed in Table 3. Thus each land use category would have a certain proportion of its total area within each of nine different slope & soil types. The total areas of each category that fell within the particular slope and soil type were determined in ArcMap by geospatially intersecting with the land use, soil and slope layers. For example, 11,904m^2 of close small houses was determined to intersect with slope >4° and soil type ‘C’ (clay, silt, mud or rock). This area was then multiplied by the runoff coefficient expected for that category, in this case 0.3 (ie. approximately 30% of the rainfall generating runoff), giving a result for imperviousness of close small houses with slope >4° and soil type ‘C’ of 3,571.4m^2. This was then calculated for each category and the areas summed to give catchment imperviousness, or rather, the catchment-wide runoff coefficient, which is a close approximation of imperviousness.

The annual rainfall used to estimate annual runoff volumes was 682 mm/year, based on the Finnish Meteorological Institute’s “Tilastoja Suomen Ilmastosta” 1981-2010 average for the area (Pirinen *et. al.* 2012).

2.5.3. Estimating future imperviousness

A number of master plans were obtained from Suvi Tyynilä, the Lead Architect of the KUNTA development at the City of Helsinki Planning Department. Some of these were georeferenced and overlaid onto maps that had been made already in ArcGIS. Following this, all the impervious surfaces were digitised and the total areas added to the figures for current imperviousness in the catchment, while removing the infrastructure that will be destroyed as part of the development. The stormwater system was digitised to the best current approximation, as the development has not yet begun and the stormwater system not yet finalised as of September 2012. The new catchment border was estimated, as the new buildings, roads, and their connections to the new and existing stormwater pipes will change the current border. It must be stressed that the total imperviousness figures and the layout of the new catchment border are only the best guess at this stage of the development. Unfortunately, as the new development will not begin until 2013 at the earliest, and Effective Impervious Area cannot be determined from the plans alone, this paper does not contain an estimate of it. However, some inferences can be made, and are reported in the results.

3. Results

3.1. Water quality - Automatic monitoring probe

Water quality in Hakuninmaanoja exhibits a range of changes following rain events. In this catchment the changes are usually rapid and short-lived. For example, water temperature in Hakuninmaanoja can increase by up to 4°C in less than 30 minutes during a big rainstorm (ie. greater than 15mm event) and around 2°C during a small event (<4mm), but returns to normal after between three to five hours (Fig. 16). This represents a strong temperature fluctuation in a short space of time. The average and maximum water temperatures recorded during the sampling period reflect the time of year of sampling (summer to autumn). Water temperature also exhibits a diurnal pattern with maxima during the day and minima at night, in response to air temperatures.

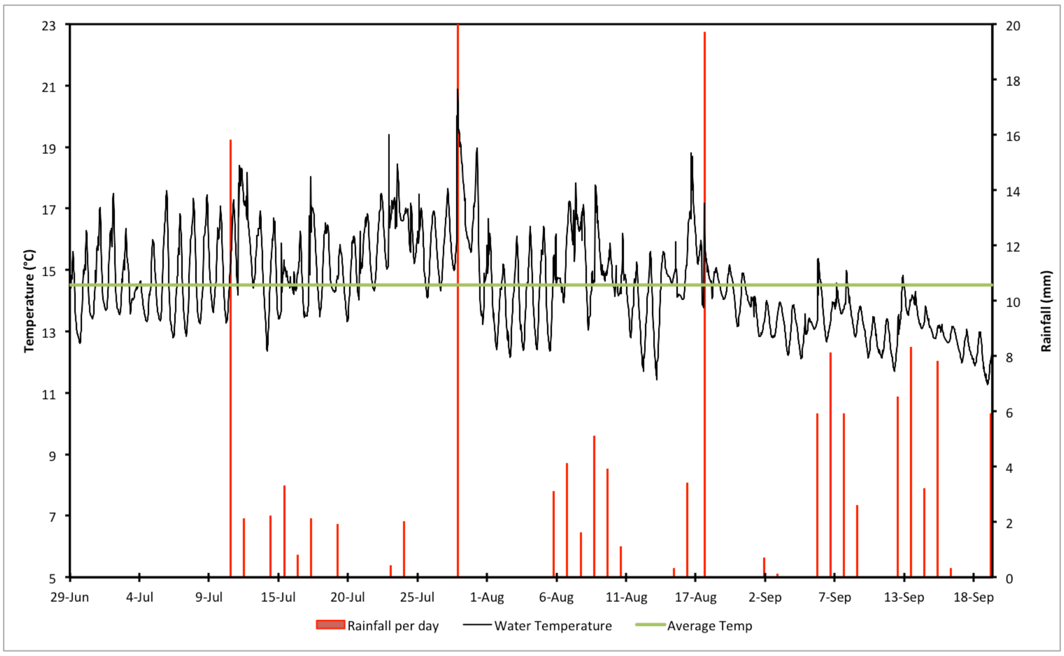


Figure 16. Water temperature data from YSI probe, showing diurnal pattern and response to rain events.

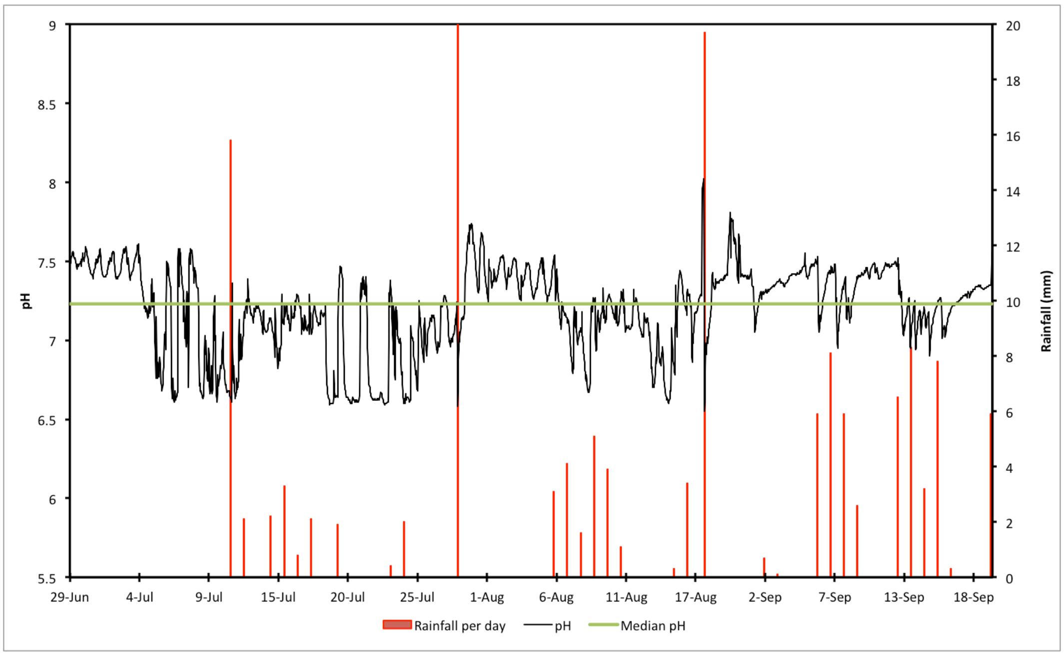


Figure 17. pH and rainfall from YSI probe during sampling period.

The median pH of Hakuninmaanoja at the sampling site is almost neutral, and tends to become more slightly more basic following rainfall (Fig. 17), but also fluctuates without rainfall, indicating connection with another variable. Electrical conductivity (a measure of total dissolved salts) decreases following rainfall (due to dilution) (Fig. 18), and shows a clear trend of higher conductivity during the warmest part of the sampling period (June & July), with a decreasing trend into the autumn.

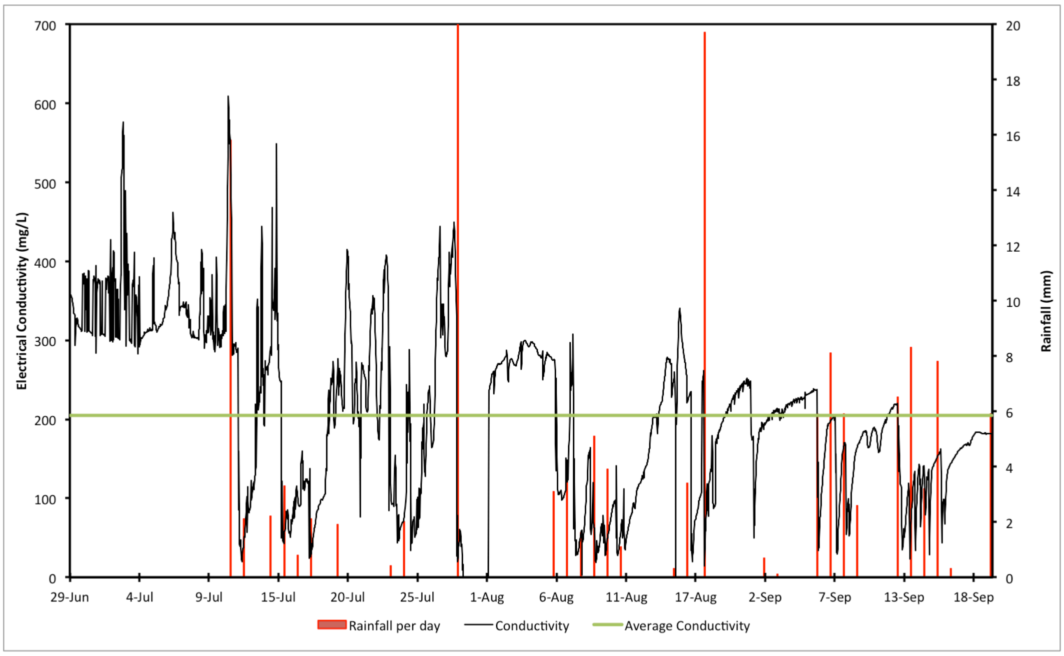


Figure 18. Electrical conductivity and rainfall data from entire sampling period.

The results for the nitrate probe should be viewed with caution: it is suspected that the very high figures (especially when compared with the laboratory-analysed hand samples) mean that the probe was malfunctioning for a large part of the time (Table 4). The highest readings for nitrate was extremely high compared to the average, as well as the deviation around the mean. This is seen to be indicative of the level of functionality of that particular probe. Similarly, the results for depth should be taken carefully, as the depth probe was without a reference point where it sits in relation to water level. However, it is clear that Hakuninmaanoja is a small stream, having a maximum depth over the sample period of just 81cm (Table 4) and an average depth of only 15cm.

Table 4. Descriptive statistics using the continuous water quality monitoring data. Note: averages are calculated without the data from the sediment event as described below. * indicates unreliable figures.

	Average	Max	Min	St. Dev
Temperature (°C)	14.51	20.88	11.27	1.48
Electrical Conductivity/Total Dissolved Salts (mg/L)	204.85	609.00	0	110.64
Depth (m)	0.15	0.81	0.01	0.12
pH	7.19	8.02	6.55	0.27
Oxidation Reduction	402.31	499.30	-24.40	115.99

Potential (mV)				
Nitrate* (mg/L)	223.24	766.80	45.21	126.65
Turbidity (NTU)	21.92	1080.80	0.30	61.43
Dissolved Oxygen Saturation (%)	88.60	137.80	11.10	15.62
Dissolved Oxygen Saturation (mg/L)	9.02	13.32	1.15	1.57

Oxidation Reduction Potential measures the electrical potential of water to oxidise or reduce: generally the higher the value (in millivolts), the higher the water quality. Readings below zero indicate low levels of dissolved oxygen, making it difficult for stream organisms to survive. Conversely, readings above approximately 600mV can be considered to be so strongly oxidizing as to be lethal for most biota. As a reference, tap water is usually between +200 to +600mV. In this study the average Orp figure puts Hakuninmaanoja stream water in the middle of that range. The minimum Orp is below zero, although this only occurred one time in three months.

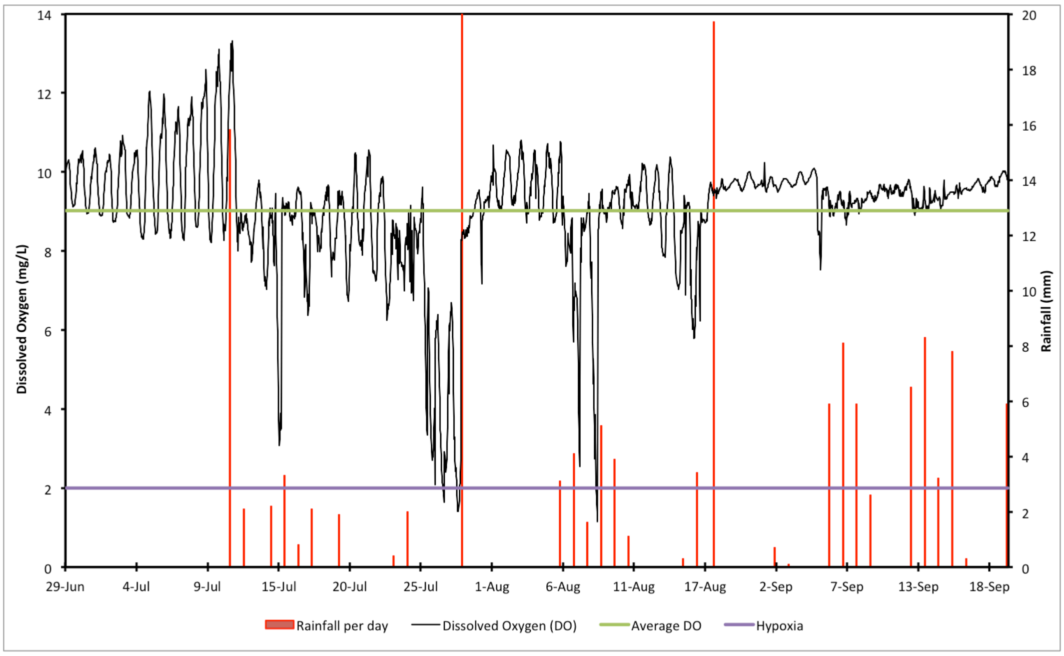


Figure 19. Dissolved oxygen (mg/L) and rainfall over sampling period.

Dissolved oxygen tends to exhibit a diurnal response with maxima during the day and minima around midnight, but the average percentage saturation is quite high at 88% (Table 4). Measured in milligrams per litre the average dissolved oxygen over the sampling period is 9 mg/L, however the minimum level of dissolved oxygen was just 1.15 mg/L, which is below the 2 mg/L level where hypoxia strongly affects most biota. This occurred on four occasions during the sampling period and was low on another two occasions, but did not appear to be connected to rain events. During rain events dissolved oxygen tends to increase in Hakuninmaanoja at this monitoring site (Fig. 19), and appears to do so in response to, or at least together with the diurnal water temperature fluctuations (Fig. 20). The effect is more pronounced during the warmer months of June, July and August, while decreasing into the autumn.

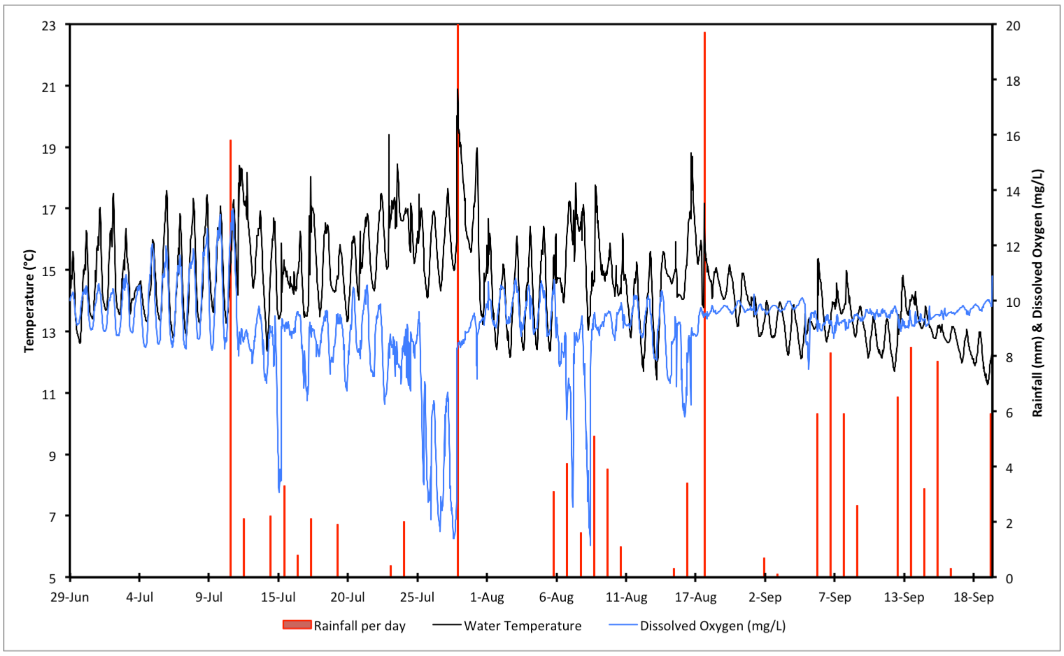


Figure 20. Graph illustrating relationship between rainfall, water temperature and dissolved oxygen in Hakuninmaanoja.

Turbidity increases in response to rainfall and the consequent washing of sediment from upstream and surrounding streets via the stormwater system, however the high figures from 1st - 5th September with no attendant rainfall (Fig. 21) are most likely due to the construction of the weir and monitoring station building, which was being finished at this time.

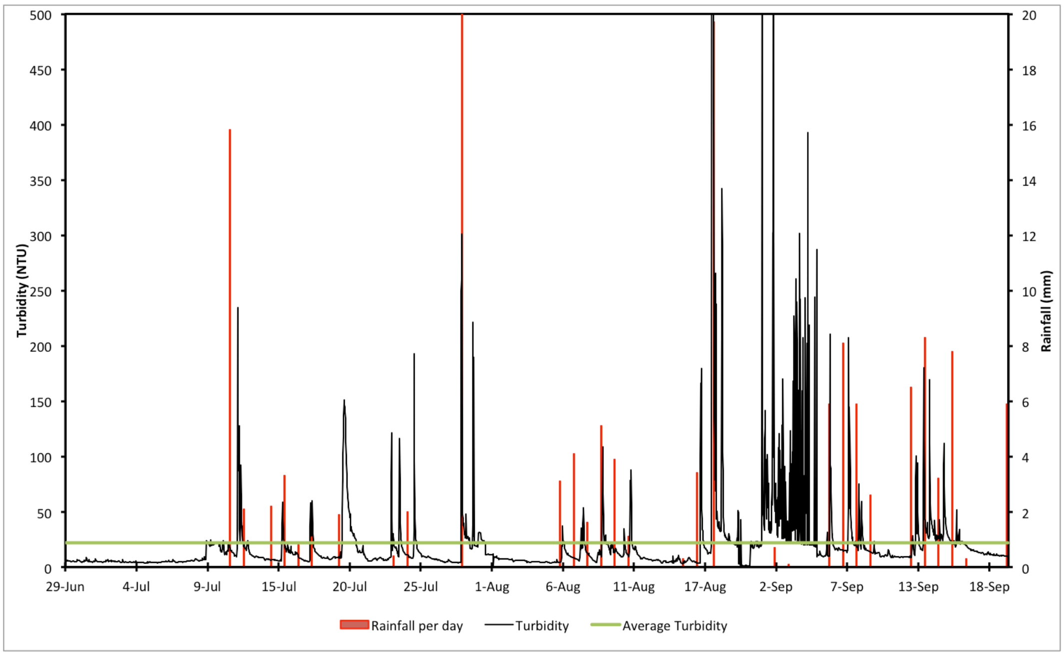


Figure 21. Turbidity data and rainfall from automatic monitoring probe over three months.

Event-based results serve to illustrate the “flashy” nature of urban catchments and provide evidence for the rapid water chemistry changes that occur during rainstorms. The event on 11th July was a large summer rainstorm of 15.80mm. In the absence of hourly rainfall totals, and in order to standardise rainfall correlations with the water quality data, daily rainfall totals from Helsinki-Vantaa airport were set at 12:00 each day. However, the 30-minute intervals of water quality measurements from the YSI probe allow a more precise picture to emerge of the water quality changes and their response to rainfall at the monitoring site. These results show that the depth increased by 70% between 02:30 and 03:30 on 12th July, in contrast to the time at which rainfall was standardised. Aside from the large depth increase, turbidity increased by 92% in the first 30 minutes of the event, and nitrate increased by 72% and over 100% in first hour (although nitrate figures themselves are likely to be inaccurate as mentioned earlier). pH became slightly more basic as the depth increased. This result was also seen after several different rain events (Fig. 17, p.43). Conductivity also decreased by 70% during the first 30 minutes, and this effect was seen during almost every rain event (Fig. 18, p.44). Water quality changes are likely to be even more rapid than within 30 minutes, however the accuracy in this study is limited by the 30 minute reading intervals.

On 22nd August, it was discovered that something had occurred upstream which had completely covered the probe and streambed at the site with fine clay sediment to a depth of approximately 5cm (Fig. 22).

Figure 22. The YSI probe before and after the sediment event. Left photo, July 2011, right photo 22nd August 2011.

This caused the probe parameters to record incorrectly or stop working entirely for five days from 17th August between 14:30 and 15:00, until it was cleaned upon discovery by the researcher at 15:00 on 22nd August. As the probe was completely full of sediment over this time, none of the data can be considered accurate except for the last correct reading, the first of the event and the first one after the probe was cleaned (Table. 5).

Table 5. Probe data before, during and after the sediment event. * indicates median rather than average.

	Temp (°C)	EC (mg/L)	Depth (m)	pH	Orp (mV)	NO3- (mg/L)	Turb (NTU)	DOsat (%)	DO (mg/L)
Last normal reading (17.08.12 @ 14.30)	15.76	141.5	0.108	7.28	432.1	168.3	18.7	97.7	9.69
First reading of the event (17.08.12 @ 15:00)	12.75	311	0.108	6.57	371.9	124.1	0.3	9.2	0.98
First reading after cleaning (22.08.12 @ 16:00)	13.86	246.5	0.086	7.94	342.9	185.4	1080.6	92.4	9.53
Average over sampling period	14.51	210.76	0.15	7.19*	402.31	223.24	21.92	88.60	9.02

It took over one hour to clean the probe as the sediment was very fine and with sticky clay texture. However it is not just the massive influx of sediment which impacted the stream, but also the temperature shock: water temperature decreased by 3°C within the first thirty minutes of the event to well below average for the entire sampling period. While the dissolved oxygen seems to have dropped to zero at the start of the event, unfortunately it cannot be determined for certain that the reading is correct because the probe was covered with sediment.

The researcher managed to locate the source of the sediment by walking upstream, and found a property being drilled for geothermal heating. The sediment and cold water from the hole was being pumped directly into the stormwater system and from there into the upper tributaries of Hakuninmaanoja. This was obviously illegal and the Finnish EPA was notified and the company's details noted. A hand sample was also taken at the site on this day to further corroborate these results (see Tables 6 & 7, Fig. 26, pp. 52-3).

The work at the property ended on that same day and a large rainfall event (19.70mm) on the evening of 22nd August served to flush all the sediment and other pollutants downstream into Mätäjoki and eventually into the Gulf of Finland. Moreover, the effect of the rainfall was to suddenly increase the temperature of the stream by 4°C between 19:00 and 19:30 on the evening of the 22nd Aug (Fig. 23). The stream therefore experienced two strong temperature shocks within five days: firstly very cold water coming from the drilling site upstream, and secondly warm water coming from surrounding streets during the large rain event. To illustrate the size of the rain event further, the depth of the stream increased by 37cm within 30 minutes (82% increase), and conductivity decreased by 90% (Fig. 24). Turbidity decreased from its maximum of 1080 NTUs by 62% in the first 30 minutes and almost 80% within the hour (Fig. 25), showing how quickly the huge amount of sediment was flushed downstream. This maximum reading was also the largest during the entire sampling period.

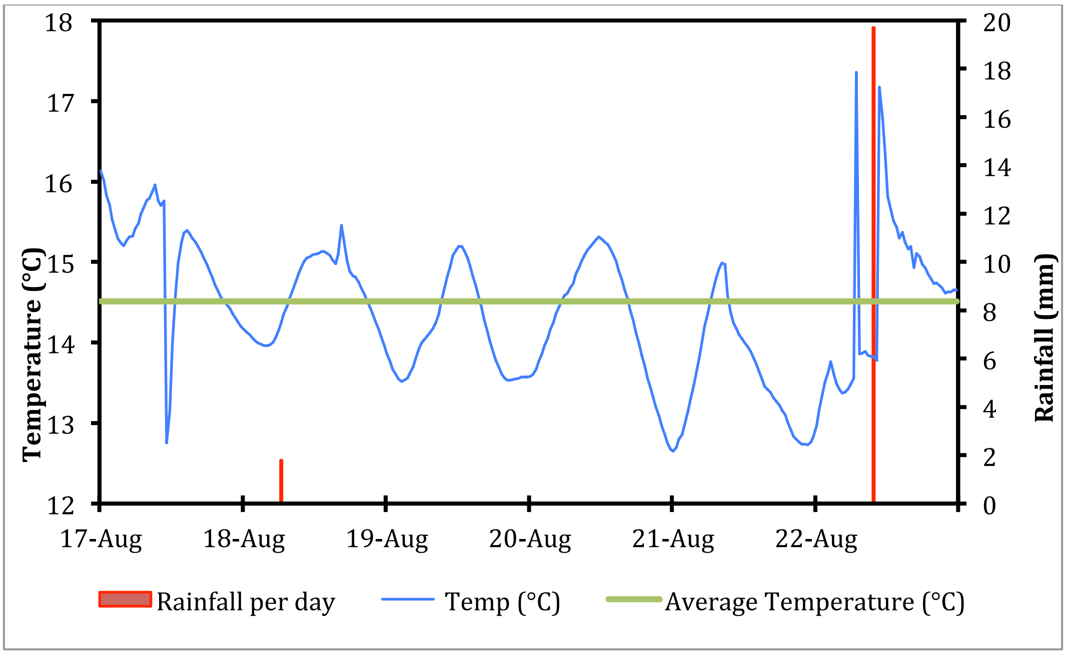


Figure 23. Water temperature before, during and after the sediment event and large rainfall event. Note: the temperature reading of 17.36°C just before the large rain event on 22nd Aug is actually air temperature due to the researcher cleaning the probe at that time.

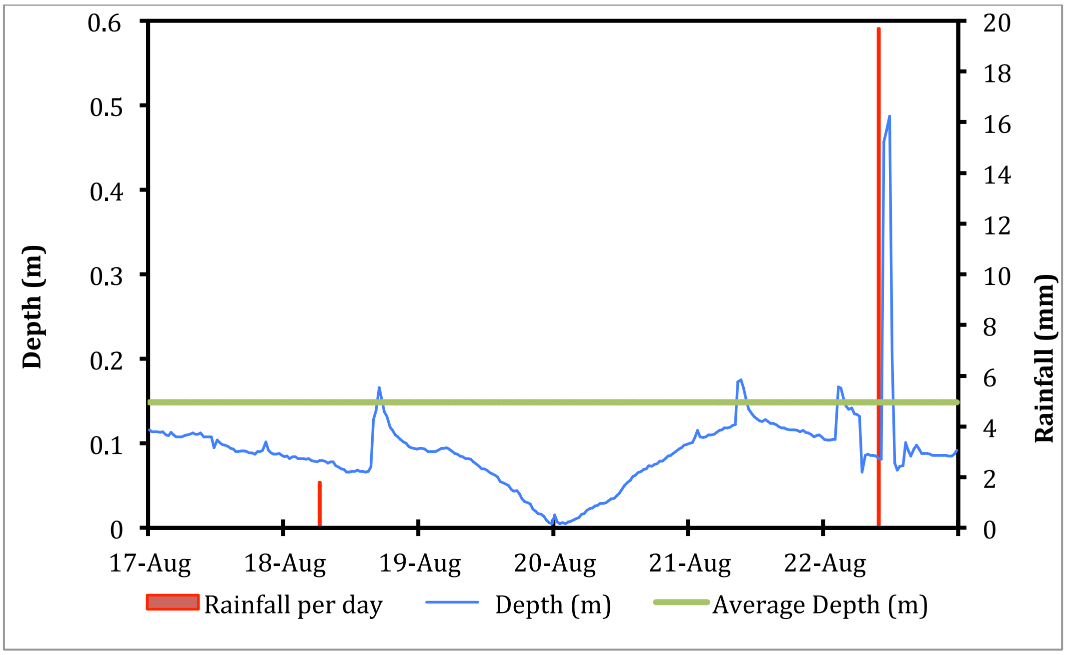


Figure 24. Stream depth at sampling site before, during and after sediment event and large rainfall event.

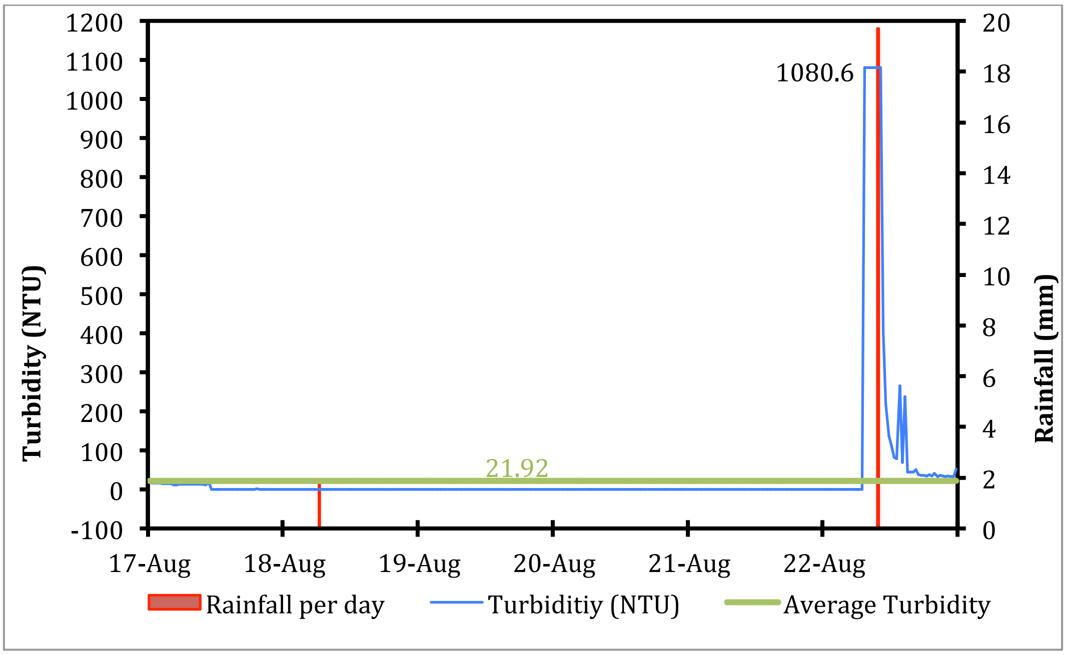


Figure 25. Turbidity before, during and after sediment event and large rainfall event.

The possible effects of this massive influx of sediment, and in particular the temperature and possible oxygen "shocks" on the stream and its organisms will be covered in the discussion.

3.2. Water quality - Sampling analysis

Hand samples analysis supported the suspected inaccuracy of the nitrogen probe, as the more stringent laboratory testing showed maximum nitrate concentration from seventeen samples of just over 6 mg/L and an average of 2.8 mg/L, compared with a maximum reading from the probe of 766 mg/L and an average of 233 mg/L (Tables 6 & 7).

Table 6. Selected hand samples analysis, descriptive statistics. Note: in red are results from the sediment event sample.

	Suspended Solids (mg/L)	Loss on ignition (%)	Organic Solids (mg/L)	Dissolved Solids (mg/L)	TN (mg/L)	TP (mg/L)	Na (mg/L)
Average without sediment event	39.42	24.57	8.13	205.20	1.33	0.10	34.58
Average with sediment event	92.64	23.31	10.13	211.06	1.33	0.14	37.92
Max	891.00	41.78	40.00	352.00	2.55	0.76	91.28
Min	10.66	4.49	2.30	63.00	0.60	0.04	9.02

Table 7. Selected hand samples analysis, descriptive statistics. Note: in red are results from the sediment event sample.

	K (mg/L)	Ca (mg/L)	Mg (mg/L)	F (mg/L)	Cl (mg/L)	Nitrate (mg/L)	Sulphate (mg/L)
Average without sediment event	3.24	21.20	4.17	0.26	54.18	2.81	15.49
Average with sediment event	3.57	21.28	4.32	0.33	53.82	2.76	17.21
Max	8.73	35.06	7.36	1.47	96.84	6.13	44.70
Min	1.68	6.87	1.23	0.14	12.13	0.39	5.68

The sediment event had a large effect on the pollutant analysis, and was therefore examined separately. Unsurprisingly the sample from that day contained very large concentrations of suspended sediment, organic solids, total phosphorus, sodium and sulphate, and the largest recorded concentrations of potassium and fluoride (Tables. 6 & 7 above, in red; illustrated in Fig. 26 below). The result for total nitrogen was so high for this sample as to be off the scale and is therefore not indicated in red in Table 6 (though it would have been by far the highest), making the averages with and without the sediment event data the same.

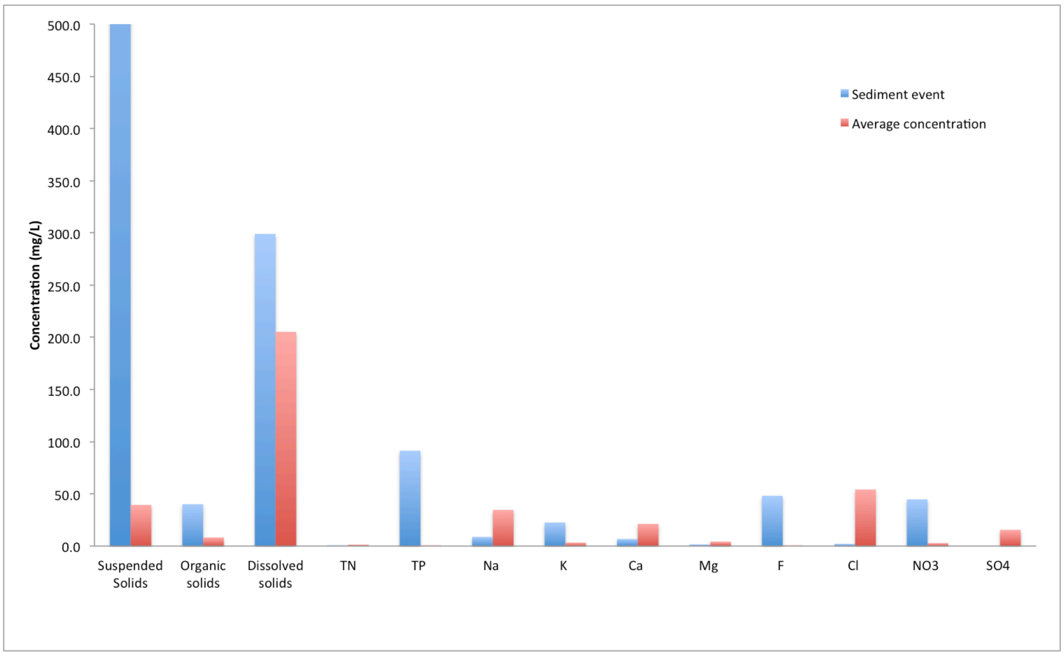
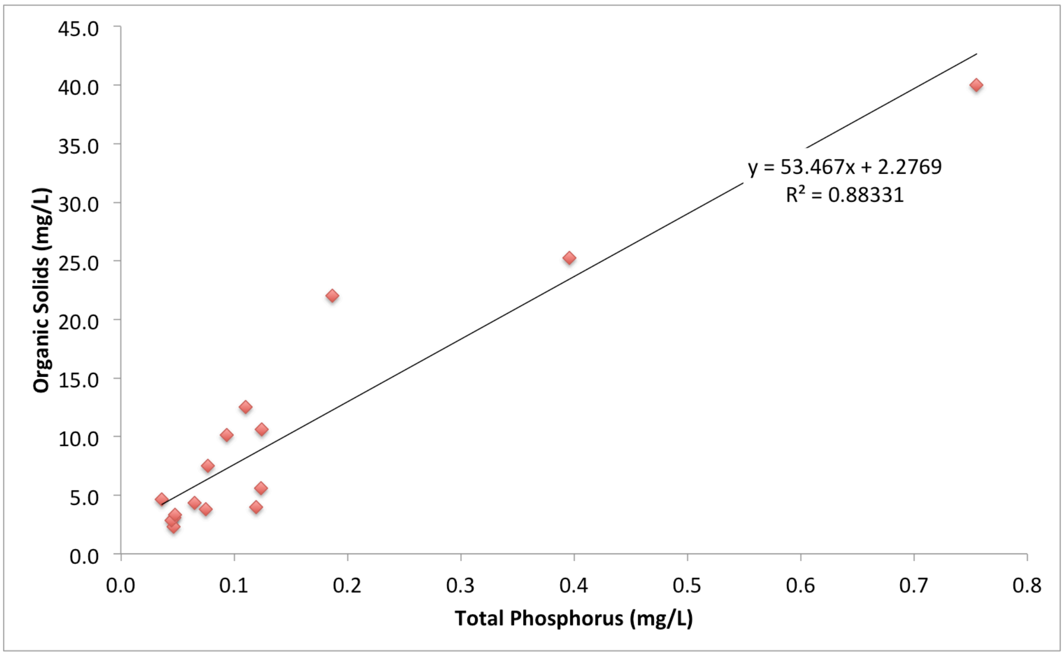


Figure 26. Comparison of sediment event concentrations and average concentrations of pollutants from hand samples.

Sampling analysis also showed a relatively strong positive correlation between organic solids and total phosphorus, as well as total nitrogen (albeit weaker) (Fig. 27). There were no correlations above $r^2 = 0.26$ between rainfall and any of the other water quality parameters measured.



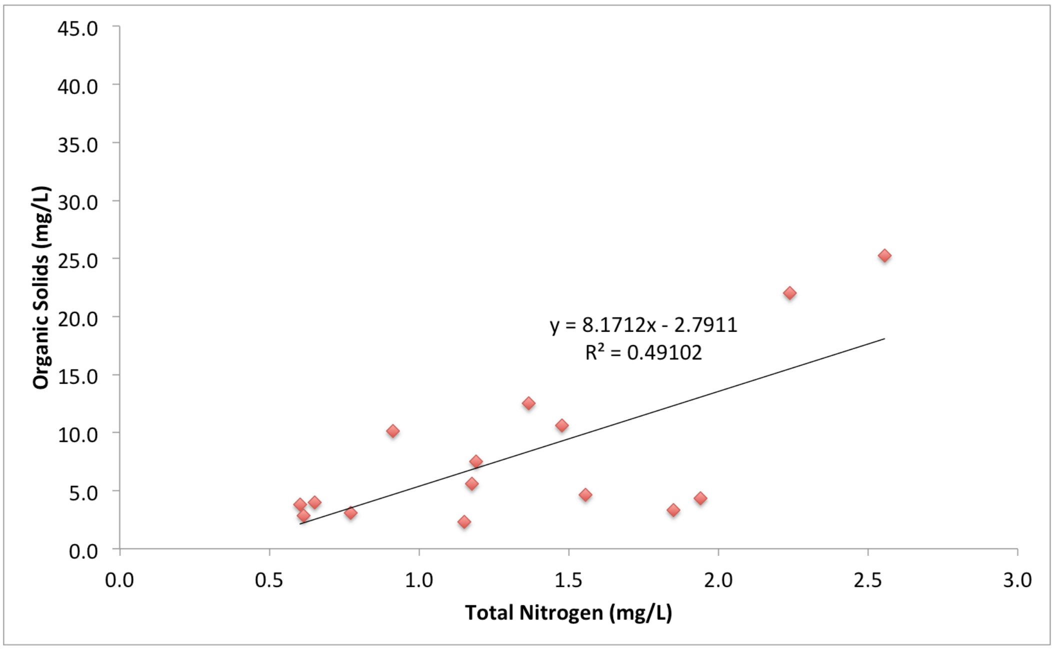


Figure 27. Correlation between organic solids and total phosphorus (upper) and total nitrogen (lower) from sampling analysis.

3.3. Present Impervious Area

The field survey and subsequent analysis with ArcGIS software resulted in a determination of the catchment to have Total Impervious Area of 22%, and Effective Impervious Area of 15.1% (Table. 8).

Table 8. TIA and EIA area and percentages.

Land use	Total impervious area (TIA) (m2)	Effective impervious area (EIA) (m2)	% Connectivity
Driveways	80,790.97	60,315.37	74.66
Roads	90,982.20	71,308.78	78.38
Buildings	117,843.51	70,822.25	60.10
Total	289,616.68	202,446.40	69.90
Catchment area	**1,341,020.00**	**202,446.40**	15.10
%TIA	**22**	**If all roads & driveways = 100% EIA**	**18**

The catchment as a whole is 70% connected to the stormwater system, with the transport component showing a greater degree of connectivity to the stormwater system than the rooftop component. If all roads and driveways are treated as 100% connected to the stormwater system (as occurs in some designations of imperviousness due to simplicity), EIA rises to 18% of the catchment area.

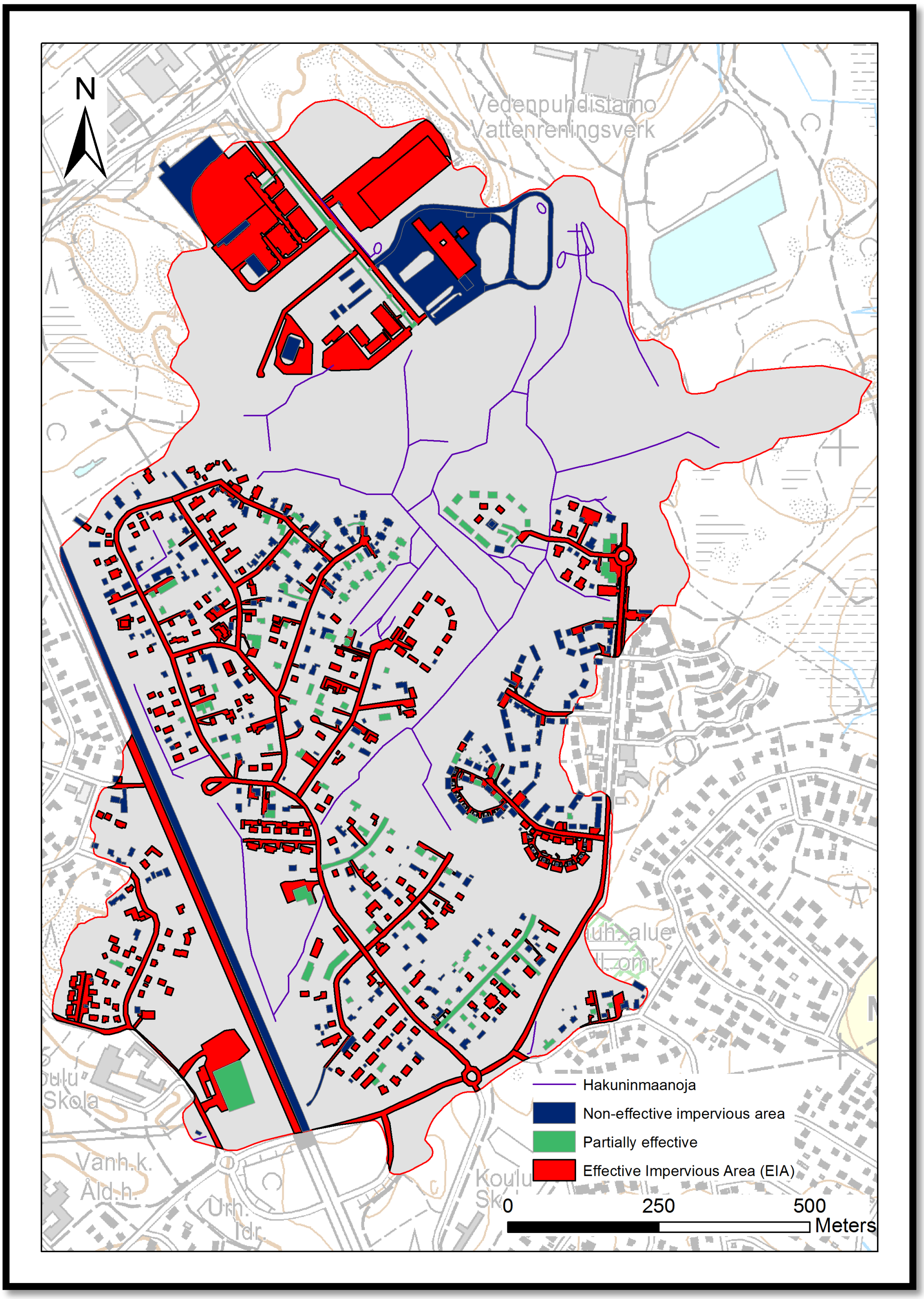


Figure 28. Map illustrating the distribution and types of impervious area within the Hakuninmaanoja catchment (Peruskartta [Basic map] 1:20,000, UL4134L, 2010).

This map illustrates the distribution and types of impervious area in the catchment (Fig. 28). This includes all hard surfaces (driveways, parking lots, roads and buildings), however all of the features are grouped in this map only by type of imperviousness, rather than by their distinct characteristics. It is clear from this map that most roads are EIA, whereas the roads coloured green are gravel roads with stormwater pipes underneath. The industrial area in the northern part of the catchment is mostly EIA, which is indicative of that land use, but there are also large areas of non-connected asphalt. The large surface areas of factory and warehouse buildings generate a lot of rooftop runoff, which is traditionally dealt with using the stormwater system. The smaller buildings, which are mostly pre-war single-family houses, are often not connected to the stormwater system and are coloured blue to indicate non-effective impervious area. The water from these rooftops runs onto the lawn or is collected in rain barrels during the warmer months. The highway (Hämeenlinnanväylä) is EIA in the southbound direction only because the stormwater pipes are located on that side. The northbound lane drains to the median strip or to the road shoulder on that other side, and from there to a grassy and lightly wooded area. In very heavy rains the runoff from this side of the highway may reach parts of the stream closest to it.

Table 9. Breakdown of TIA and EIA components. Runoff vol. rounded to nearest hundred thousand litres.

TIA				
	Area (m2)	**% of TIA**	**% of catchment**	**Estimated runoff vol. per year (L)**
Transport component	171,773.17	59.31	12.81	117,100,000
Rooftops	117,843.51	40.69	8.79	80,400,000
Total	289,616.68			197,500,000

EIA				
	Area (m2)	**% of EIA**	**% of catchment**	**Estimated runoff vol. per year (L)**
Transport component	131,624.15	65.02	9.82	89,700,000
Rooftops	70,822.25	34.98	5.28	48,300,000
Total	202,446.40			138,000,000

Whereas the ratio of transport infrastructure area to rooftops is approximately 60:40, the transport fraction is also more connected to the stormwater system than the rooftops, constituting approximately 65% of the EIA (Table. 9). This is also reflected in the estimated runoff volumes per year from each category of TIA and EIA.

3.4. Land use-categorised imperviousness

The average catchment-wide runoff coefficient obtained by this method was Rv=0.32, or approximately 28% Total Impervious Area (at low levels of imperviousness, runoff coefficients are higher than % impervious area due to influence of soils and slopes), which is higher than the 22% reported for TIA and almost double that reported for EIA (15%) (Table 8). Interestingly, the largest portion of the runoff that would come from this catchment during a rain event is from the forested area, however this is because forest covers 72% of the catchment, and is mostly located on steep and rocky soils, leading to a greater runoff coefficient than would usually be the case for forested areas.

The largest fraction of runoff from the urban land use is from asphalt transport areas (roads and driveways) (Rv=0.86), which occupy approximately 12% of the total catchment area, followed by industrial areas (Rv=0.68). All buildings taken together would generate approximately 32,700,000L/yr runoff, and all transport areas (gravel and asphalt) would generate approximately 102,500,000L/yr.

Table 10. Land use categorised runoff coefficients and estimated yearly runoff for Hakuninmaanoja catchment.

Land use category	% of catchment area	Average Runoff coefficient	Estimated runoff volume per year (L)
Close small houses	3.48	0.23	**7,355,000**
Very close small houses	0.66	0.32	**1,950,000**
Rowhouses	1.74	0.53	**8,412,000**
Industrial	2.42	0.68	**15,054,000**
Forest	72.41	0.20	**129,140,000**
Transport areas: gravel	1.41	0.48	**6,126,000**
Lawn	4.63	0.36	**15,233,000**

Transport areas: asphalt	12.29	0.86	**96,420,000**
Water	0.96	1	**8,762,000**
Whole catchment	**100**	**0.32**	**288,457,000**

3.5. Projected future impervious area

Table 11. Current & projected imperviousness for Hakuninmaanoja catchment.

	Pre KUNTA	Post KUNTA	
	TIA (m2)	**TIA (m2)**	**% increase from existing**
Transport	171,773.17	206,053.18	16
Rooftops	117,843.51	168,224.03	30
Total	291,272.01	374,277.21	22
Catchment area	1,341,020.00	1,255,930.00	-6
% TIA	**22**	**30**	8

Following build-out of the KUNTA development, catchment imperviousness (TIA) will rise to approximately 30%, including 16% more transport related imperviousness and 30% more rooftop imperviousness (Table 11). Hidden in these figures however, is the fact that the development will remove almost 18,000m^2 of buildings and 61,500m^2 of transport infrastructure, which offsets to some degree the large increases in urban features added to the landscape of the catchment. Thus although the KUNTA development will add 54% more transport related imperviousness and 57% more rooftop imperviousness onto the existing catchment, this will be reduced by the removal of many buildings and roads in the area to be built (Fig. 29). Note however that these figures assume that the construction phase will remove all existing roads and paths that might lie in the same location as new roads (ie. the site is completely cleared prior to construction).

The KUNTA development will be built across the headwaters of Hakuninmaanoja. This means that several tributaries, wetlands and ponds lie directly in the path of new buildings and roads. Moreover, the development calls for three areas of stormwater detention ponds to be created between the existing southern residential buildings and KUNTA development to the north, which will alter the natural stream channel and hydrology. Based on the location of new infrastructure, an estimation proposed here is that approximately 2.7km of

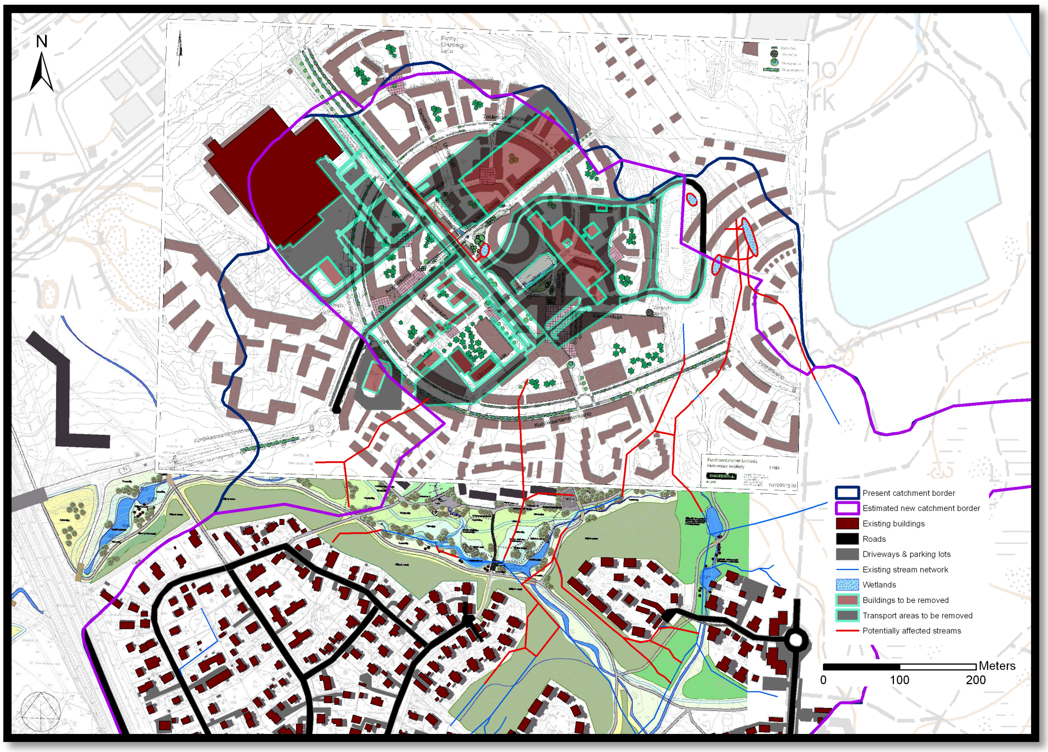


Figure 29. KUNTA development plan (Ramboll 2011, Kuninkaantammen keskusta hulevesien käsittely [Kuninkaantammi stormwater treatment plan] and the stormwater detention ponds plan (Pöyry 2011, Helene Schjerfbeckin Puiston viitesuunnitelma [Helene Schjerfbeck Park Reference Plan] overlaid onto existing catchment, showing infrastructure to be removed, potentially affected streams and estimated new catchment border (Peruskartta [Basic map] 1:20,000, UL4134L, 2010).

headwater streams will be affected by this development, either by being buried in pipes, removed entirely with earthworks, or altered as part of the stormwater management strategy (Fig. 29, in red). This will alter the natural flow pathways and hydrology of a large section of the headwaters of Hakuninmaanoja.

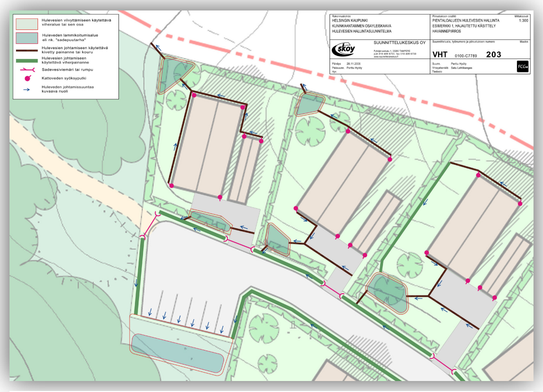


Figure 30. Example of raingarden stormwater system to be used in KUNTA development. Source: Suunnittelukeskus OY (2007).

The catchment area itself is estimated to decrease in size by approximately 6% following the full build-out of the KUNTA development, due to alteration and removal of existing infrastructure across the catchment border (Table. 11; Fig. 29.). The new development is expected to house approximately 3000 people within the Hakuninmaanoja catchment (approximately 5000 within the whole development), meaning the population will increase to almost 5000 people from the current 1,906. This increase combined with a smaller catchment area will mean that the population density will likely more than double from 1,422/km^2 to approximately 3,893/km^2.

While the post-KUNTA Effective Impervious Area was not able to be determined during the field survey because it does not exist yet, it is tentatively assumed that it will increase roughly in proportion to the increase in TIA, making it only a few percentage points larger than the current figure of 15%. This is due to two main reasons. Firstly, the new development will remove much of the industrial area in the north of the catchment in order to build the development, keeping the amount of imperviousness relatively similar in the process. Secondly, almost every new building in the development will use raingardens to infiltrate rooftop runoff (examples in Figs. 30 & 31), after which the water is led to one of three stormwater detention ponds in the central part of the catchment (to be called Helene Schjerfbeck Park). Street runoff uses a combination of green infrastructure such as grassed

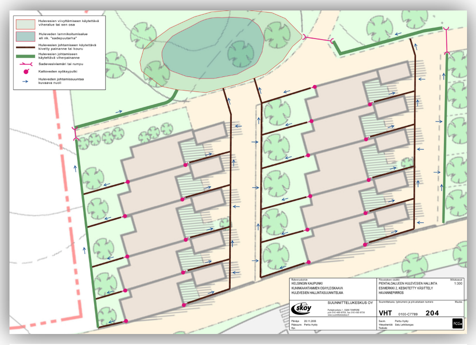


Figure 31. Example of raingarden to be used in KUNTA. Source: Suunnittelukeskus OY (2007).

and stone-lined swales, as well as traditional stormwater pipes, however the water which does not infiltrate will still travel to one of the stormwater detention ponds. After leaving the pond the central and western ponds will take roughly two-thirds of the stormwater, after which it will end up in Hakuninmaanoja, while the eastern pond will take approximately one-third, after which it will leave the catchment to travel directly to Mätäjoki (Fig. 29, p.59).

Table 12 shows the estimated runoff volumes using TIA before and after the KUNTA development. Overall a 22% increase is expected, however it should be noted that using TIA to estimate runoff volumes often leads to overestimation, due to the fraction of non-effective impervious area which does not usually lead to runoff. Moreover, these runoff volume estimates are only from the impervious area, in contrast to the Land Use Categories method where runoff from pervious areas was also calculated. The reason for this is that during the field survey, only impervious areas were surveyed due to time limitations.

Table 12. Estimated runoff volumes per year from TIA, pre and post-KUNTA development.

	Pre-KUNTA (L/yr)	**Post-KUNTA (L/yr)**	**% increase**
Transport	117,100,000	139,400,000	16
Rooftops	80,300,000	114,700,000	30
Total	197,400,000	254,100,000	22

4. Discussion

Generally the current water quality in Hakuninmaanoja is quite satisfactory in relation to other streams in Helsinki (Ruth 2003; 2004), however there are some causes for concern, particularly the potential for ‘shock’ stress on organisms due to rapid water quality (in particular temperature and sediments) and quantity changes, which are classic symptoms of the “urban stream syndrome” (Walsh *et.*

al. 2005). These changes may increase in frequency and intensity following further watershed development, depending on the effectiveness of the stormwater management techniques planned for the KUNTA development. TIA was determined by field survey to be 22% and EIA at slightly over 15% in the current Hakuninmaanoja catchment. This is quite low when compared to many other, highly urban catchments (TIA 50-99%) and reflects the suburban nature of the catchment (Allan 2004). However, if all roads and driveways were to be designated as EIA (as often occurs due to time and budget constraints), the catchment EIA percentage rises by 3%. This difference is more important for low-density catchments where some roads are still unconnected. A 30% increase in runoff volumes from buildings is expected following the development of KUNTA, accounting for the large increase in population, whereas only a 15% increase in runoff from transport areas is expected, due to the KUNTA development site already containing a large area of transport infrastructure, and that car parking spaces will be mostly built underground. Overall, a 22% increase in runoff volume is expected following the development of KUNTA.

The water quality monitoring in this project represents a baseline survey of the water quality in Hakuninmaanoja prior to the development of KUNTA. As such, no earlier data exists for comparison of the water quality of this particular stream (although it does exist for Mätäjoki downstream), especially of the conditions when the catchment was mostly agricultural. The benefits of this data lie in the fact that the catchment is now low density and will become medium density following the KUNTA development. This data will therefore form a baseline for future researchers to assess the changes to the chemical and hydrological conditions of Hakuninmaanoja.

One of the aims of the project was to be able to discern patterns of changes in the water quality, as future research may be able to link those changes with land use and catchment imperviousness, especially EIA. In reality this is very difficult. Diurnal patterns are relatively easy to see, however more complex patterns such as the first flush are notoriously elusive (Goonetilleke & Thomas 2003). Several important factors prevent major correlations being drawn between land use, catchment imperviousness and water quality in this study. Firstly, without a consistent measurement of discharge at the monitoring site, the connection between land use, rainfall and water quality cannot be determined, and estimates of runoff volumes cannot be verified using real world data. Unfortunately the later than expected completion of the monitoring station and weir prevented discharge from being quantified for this study.

Secondly, rainfall data was provided to the project from Helsinki-Vantaa airport (approx. 6km NE of monitoring site), and as a daily total rather than hourly. Rainfall in this catchment and in southern Finland in general can be considered very localised: there were some instances during the field survey where it was raining very heavily in one place and completely dry only 100m away. This makes it difficult to correlate with rainfall in the Hakuninmaanoja catchment which may be slightly different in amount and intensity than at the airport, and difficult to correlate with the water quality probe that measured every 30 minutes. In order to standardise, daily rainfall totals were set at 12:00 each day. However, as the 30-minute sampling intervals allow the actual time of water quality changes to be seen independent of that standardisation, the time of water quality changes due to that rainfall can be seen (although the amount of rainfall responsible for those changes can only be seen as the daily total). These factors prevent a real world assessment of catchment lag time and discharge volumes.

However, there is still value in visually correlating a large rainfall event with changes in one or more parameters of the automatic monitoring probe, which demonstrates the rapid water quality changes that occur in urban streams. During the sampling period there were only four rainfall events over 10mm in a 24hr period. This is typical of southern Finland where most rainfall events are small and not very intense compared with other temperate climate areas. Precipitation mainly falls as snow. Small rain events are not likely to cause hydraulic stress or morphological changes to streams, but may still affect biota through chemical and thermal changes (Walsh *et. al.* 2005).

Temperature affects many aspects of stream ecology and water chemistry, dictating the type of biotic assemblages present in a particular stream and their activity levels, ability to compete and growth rates (Janke *et. al.* 2009). The concentrations of nutrients and in particular dissolved oxygen are affected by water temperature. Rapid temperature changes are often symptomatic of urban streams (Walsh *et. al.* 2005), where rainfall becomes warmer after thermal transfer with heat-retaining impervious surfaces, and subsequently increasing stream temperature after traveling through the stormwater system (Van Buren *et. al.* 2000). In Hakuninmaanoja and other Finnish urban streams, summer baseflow is mostly provided by cold groundwater and leaks from the water supply system (Ruth 2004). This maintains a delicate and valuable cold-water ecosystem, where organisms are adapted to narrow temperature fluctuations. Although rainfall is also usually cold in northern climates, the heat retained in impervious surfaces results in large and rapid temperature increases. The life cycles of fish species such as salmon and trout are disrupted when water temperature oscillates outside their narrow optimal range (US EPA 1999; Van Buren *et. al.* 2000), as occurred during the sediment event of 17-22nd August 2011 during the sampling period. Here the temperature dropped to 3°C below average within 30 minutes at the beginning of the event, and during the large rainfall event five days later which washed all the sediment away, water temperature increased to 4° above average within 30 minutes. A temperature rise of this much is enough to make sensitive fish avoid affected reaches of a stream (US EPA 1999). Although there are probably no adult salmon or trout in Hakuninmaanoja due to its small size, the stream could be a breeding ground for their eggs as well as habitat for prey species, and the fluctuations in temperature would affect the reproduction, growth rates and oxygen availability for those species.

The alternate side of urbanisation is a loss of infiltration capacity, and consequently less groundwater recharge, which may reduce the baseflow of such cold climate urban streams. This is important when considering not only the ecological health of urban streams, but also their aesthetic appeal to residents. If one of the goals of urban stream management is to have streams with reasonable water quality and recreational fisheries, then such temperature changes will need to be mitigated by retrofitting existing urban areas and applying WSUD to new ones.

One of the main stormwater management techniques proposed for the KUNTA development is a large area of detention ponds located between the upper part of the catchment where the development will occur and the existing urban area. This will capture much of the storm flow from the additional impervious area. Detention ponds are a type of stormwater BMP that is designed to pond stormwater and delay its entry to the stream network, reducing the sharp increases in the hydrograph often seen after urban development (US EPA 1999). As such these ponds are expected to have some depth of water most of the time. However, research suggests that creating large areas of standing water may exacerbate temperature increases by providing a large surface area to receive solar radiation (Galli 1990; Janke *et. al.* 2009). In the case of Helsinki, this effect has not been studied, although due to the climate only a relatively short period of the year would be expected to appreciably increase water temperature in this way. However, the fact that stormwater detention ponds are routinely used in stormwater management should be a cause for further research. Galli (1990) suggested that average stream temperature increased by 0.09°C for every one percent increase in catchment imperviousness (assumed to be TIA). In the context of the Hakuninmaanoja catchment, TIA is projected to increase from 22% to almost 30%, which would potentially result in a 0.72°C average temperature increase from the existing situation. This is in addition to the current situation in the catchment where temperature can rise by up to 4°C within thirty minutes. Research suggests that the metabolism, respiration and therefore oxygen requirements of aquatic organisms approximately doubles with a 10°C rise in water temperature (US EPA 1999). Using the temperature increases seen in this study as a basis, this means an almost 40% greater than normal oxygen requirement for stream biota during such events even before the KUNTA development has begun. Climate change will likely exacerbate this situation, making it increasingly difficult to maintain cold-water ecosystems in urban streams in the face of increasing urbanisation.

One way of mitigating these rapid temperature ‘shocks’ can be through developing temperature standards in the City of Helsinki Planning and Environment departments, and incorporating into regulations for developers. For example, some states in the US limit temperature rises to as low as 0.6 - 1°C (US EPA 1999). While obviously Hakuninmaanoja is too small to be a recognised cold-water fishery, the downstream Mätäjoki can be, if managed for temperature increases. Integrating EIA figures in urban planning should also allow quantification of temperature increases for a given development, helping to minimise their impact.

Levels of dissolved oxygen are quite good, averaging 88% saturation and 9 mg/L, and tend to increase following rain events. This is expected to mean that the stormwater coming to the stream is quite well oxygenated, and may be partially explained by the results of this study which calculated that the large areas of forest in the catchment contribute the greatest amount of runoff of any land use. However the direct impacts of urban stormwater are not usually thought to impact on dissolved oxygen levels in urban streams, compared to the impact of nutrient enrichment (US EPA 1999). Hypoxic conditions occurred in the stream on four occasions, one at the end of a four-day dry spell, and where the next rain event (24.30mm) coincided with an 8-fold increase in dissolved oxygen levels. One explanation for this is related to the time of year of those events: they occurred during the warmest part of the year when low discharge probably coincided with algal die-off, resulting in hypoxic conditions. The following large rainfall event may have increased nutrient input again leading to algal growth and thus high dissolved oxygen levels, although unfortunately no hand samples were taken on this day to test for nutrient levels. Dissolved oxygen also displays a diurnal pattern similar to the temperature fluctuations between day and night. This is probably due to increased biological activity of algae during the daylight hours, producing oxygen. Some species of algae were observed covering rocks in the stream, however they were not sampled. During the autumn there is less sunshine and therefore this effect is diminished. Photosynthesis also increases pH, a result seen in this study, and although causality between the two cannot be determined, it partially supports this idea.

High turbidity is problematic for benthic invertebrates & fish assemblages (Fig. 33), but also affects aesthetic qualities of urban waters, potentially reducing their visual appeal to residents in addition to reducing the recreational availability of fish species for angling enthusiasts. In Hakuninmaanoja the extremely high turbidity during the sediment event of 22nd August was reflected not only in the automatic monitoring data, but also in the water sample analysis, which returned very high sediment concentrations. This event would have had the effect of eliminating most biota downstream, until the large rain event washed the sediment into Mätäjoki. However, these effects are often temporary in urban streams as a result of colonisation and migration from upstream and downstream areas. Turbidity data for Hakuninmaanoja exhibit a similar pattern to water temperature, in that changes are very rapid and short-lived, which again can lead to shock stress in organisms. In this stream turbidity can increase by up to 100% even in response to a small rain event (1-5mm) and return to normal within two hours, a result that can often only be seen through high frequency automated monitoring.
Conversely, high turbidity reduces light penetration in the water column, and thus may help to alleviate algal blooms due to high urban inputs of nitrogen and phosphorus (Walsh *et. al.* 2005).
Generally however, in Finnish streams nutrient input tends to decrease following conversion from agricultural to urban land use, due to less input from farming activities (Ruth 2004).
The stormwater detention ponds proposed for the KUNTA development will go some way to

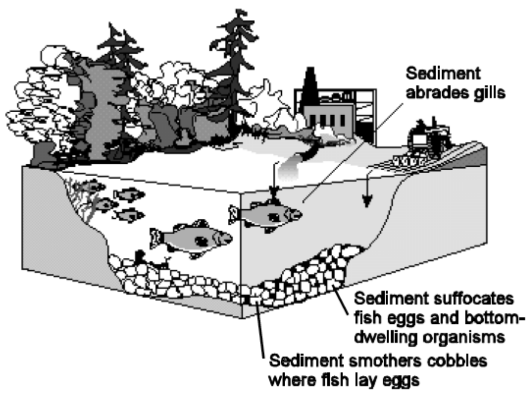


Figure 33. Illustration of effects of high sediment loads on aquatic biota. Source: US EPA 1999.

reducing these turbidity shocks, by allowing sediment to settle, and will have the added effect of trapping pollutants such as heavy metals. However, maintenance (ie. removal of sediment offsite) will be needed at least annually to prevent loss of performance of the ponds (US EPA 1999). This is especially critical considering the effects of the sediment event on Hakuninmaanoja. If this were to happen after the KUNTA development is built, the stormwater detention pond would quickly become full of sediment, reducing its effectiveness considerably and likely leading to flooding. However, as the central area of the development drains to three different ponds, it is unlikely that all three would be affected simultaneously in this situation. One solution here would be for the City of Helsinki to make sure that the relevant contractors working in the new area are aware of the purpose and function of the stormwater management techniques, and the possible effect their activities could have upon them.

Aquatic biota are also susceptible to changes in pH, for which many organisms have a narrow optimal range. pH in Hakuninmaanoja is generally within the healthy range for aquatic organisms, but tends to become more basic following rainfall events. This is generally supported by the literature, which suggests that even though urban rainfall is often acidic (in Helsinki rain can be as low as pH 4.5), it is rapidly neutralised upon contact with the salts in street dust, resulting in a buffering effect on stream pH (US EPA 1999; Goonetilleke & Thomas 2003; Ruth 2004). However, this allows metals such as the ionic forms of Cu and Pb to readily adsorb to suspended sediment, which are eventually consumed by benthic invertebrates and may concentrate up the food chain (Goonetilleke & Thomas 2003). In some cases, pH can exhibit a first flush effect, where the first few millimeters of acidic rainfall clean the streets of street dust, causing the stream to become more basic, but where the continued rainfall is no longer buffered and causes the receiving stream water to become more acidic (Ruth 2004). This may have occurred during on the day the sediment event was discovered. There was light rain during the day when the hand sample was taken, however the biggest fraction of the 19.70mm rainfall for that day must have come during the evening, as between 19:00 and 19:30 the pH, which was quite basic at 8.02, dropped sharply to 6.51 in the following hour (Fig. 34). It is hypothesised that this represents a first flush event for pH, where firstly light rain washed the streets of dust, causing the stream water to become more basic, followed by heavy rainfall which was not buffered by street dust, causing the pH to drop significantly. These events however are very site specific and should not be taken as indicative of the general pattern of pH fluctuations in urban streams.

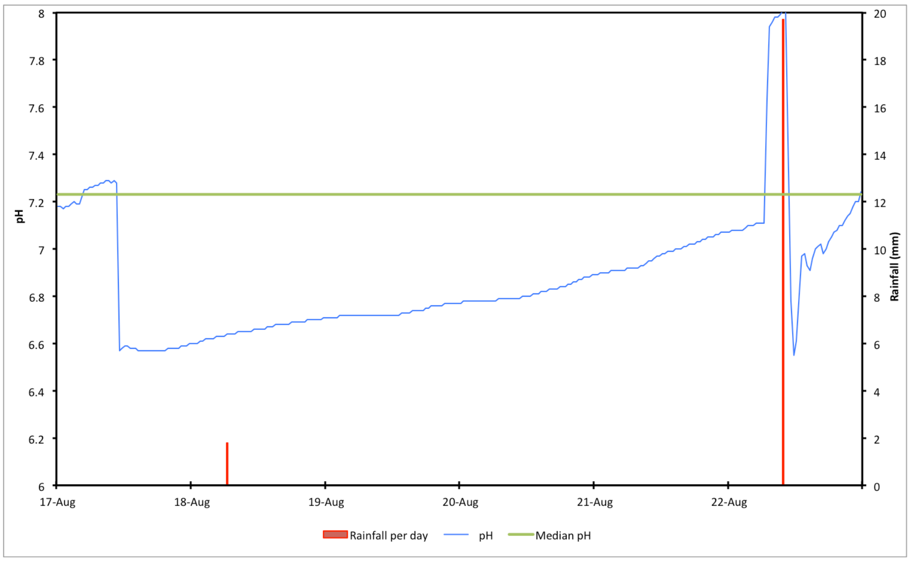


Figure 34. pH fluctuations during the sediment event and the following rainfall event.

In the cold climate context, pH is more problematic during the spring flood, where accumulated sediments, salt and metals enter streams in very high concentrations. During these events pH can become strongly acidic and deadly for aquatic life. However, in urban areas this effect is mitigated by street dust accumulation, particularly in springtime in cold climates when road wear from studded tires becomes a strong input (Ruth 2004).

Electrical conductivity, or Total Dissolved Salts, showed a decreasing trend over the sampling period (summer to autumn). This is because during the low flow periods of the year the levels are more concentrated, whereas into the autumn there is more water depth to dilute salt levels (Fig. 35). This study did not capture spring thaw salt concentrations, but summer concentrations reached as high as 600 mg/L and averaged 262 mg/L, a period not usually associated with high salt content. Autumn concentrations were more in line with that reported in the literature (Ritter *et. al.* 2002).

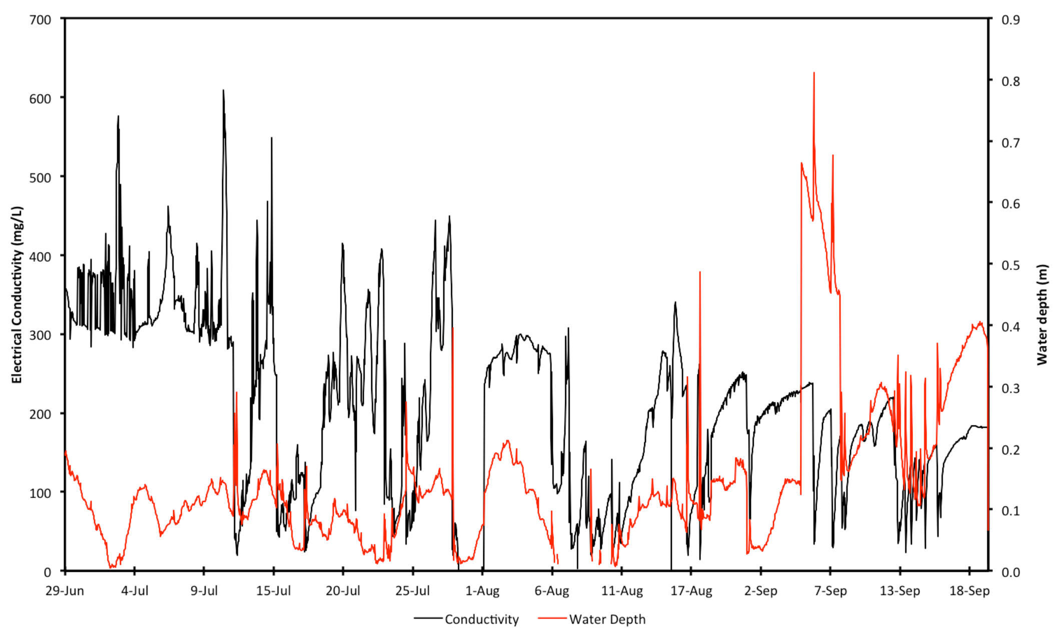


Figure 35. Graph illustrating relationship between water depth and electrical conductivity.

In general the results were rather inconclusive for the first flush effect, apart from fleetingly in the pH results, although in low-density catchments it is not expected to be a significant process. More hand sampling and analysis of metals commonly seen in first flush (eg. Cu and Pb) would have allowed this pattern to be explored with greater depth. However, access to acid-washed sampling bottles (which are necessary to analyse for metals) was a problem during the water quality monitoring in this study.

A benefit of using EIA rather than other calculations of imperviousness is that it can help to explain this variance in the relationship between pollutant concentrations and imperviousness. One problem with using TIA to describe imperviousness is that urban areas vary enormously in their connection to stormwater infrastructure due to differences in local planning laws, rainfall patterns and even culture. It has therefore been very difficult to see solid correlations between different studies. This has also been compounded by the wide variation in methodologies used to calculate imperviousness. EIA can be used to eliminate those confounding variables and allow urban areas across cities and regions to be compared more easily, however standardisation of the methods used to calculate it should be a priority for watershed managers and planners alike. This may make it easier in the future to determine patterns of water quality changes such as the first flush, and compare them across regions.

Table 13. Estimated runoff volumes for each method of determining imperviousness completed in this study.

	Land Use Categories method (L/yr)	EIA (L/yr)	TIA (L/yr)	TIA Post-KUNTA (L/yr)	% increase after development
Transport	102,500,000	89,700,000	117,100,000	139,400,000	15
Rooftops	32,700,000	48,300,000	80,400,000	114,700,000	30
Total	135,300,000	138,000,000	197,500,000	254,100,000	22

Although the correlation between imperviousness, runoff and water quality could not be determined in this study due to factors mentioned earlier that were outside the researcher's control, runoff volumes were able to be estimated for each method of determining imperviousness, as well as following the development of KUNTA (Table 13.), using the average rainfall for the area over the period 1981-2010 (682mm) (Pirinen *et. al.* 2012). Theoretically EIA should be considered the best estimate of runoff because every impervious surface in the catchment and its connection to the stormwater system were personally determined. Table 13 illustrates this by showing that if TIA is used to calculate imperviousness, runoff volumes are likely to be overestimated compared with EIA (Brabec, Schulte & Richards 2002). The difference between EIA and TIA is more pronounced for buildings than transport infrastructure, because in this low-density catchment there are many buildings but relatively few roads still unconnected to the stormwater system.

Conversely, the Land Use Categories (LUC) method predicted a smaller runoff volume coming from buildings and a larger volume from transport infrastructure, compared with EIA. Although the field survey was unquestionably more precise than the generalised runoff coefficients given by Kuusisto (2002) upon which the LUC method was based, the latter did take into account the slope and soil types, which the determinations of EIA and TIA did not. According to Schueler (2000), at low levels of imperviousness, runoff coefficients are likely to be more accurate in determining runoff volumes than percent imperviousness due to the influence of soils and slopes. However, this should be more influential in determining runoff from pervious areas and unconnected (or non-effective) impervious surfaces (which often drain to pervious areas), rather than in buildings and asphalt roads that are directly connected to the stormwater system. This means that by taking into account the soil/slope type rather than the specific connectedness of the surface, the LUC estimation of runoff volume for various types of buildings is likely an underestimation of the true figure. Moreover, a runoff data from a full year would be necessary to show whether the runoff volumes in LUC method are more accurate than those predicted by field surveyed EIA.

While there are differences between the runoff volumes expected from rooftops and transport areas using the LUC and EIA methods, the total volume of runoff expected from impervious surfaces in both methods is almost the same (Table 13). An important question to ask when determining imperviousness, is what is the right balance of accuracy, time and cost? While TIA was determined in this study using the field survey technique, it can also be determined using faster methods, including direct measurement from aerial photos and using ArcGIS software. Some research suggests that direct measurement of TIA from aerial photos can lead to a similar result as that from field survey at the catchment scale (Roy & Schuster 2009). In the case of the Hakuninmaanoja catchment, if field-surveyed TIA was used to calculate runoff volumes when designing the stormwater management infrastructure for the KUNTA development, it is likely there will be an 8% loss of accuracy compared to the figures if EIA was used, with a greater loss expected if TIA was measured differently, for example with remote sensing. To the researcher’s knowledge, the City of Helsinki had not performed a field survey of the Hakuninmaanoja catchment prior to this project. This could increase costs, in turn affecting the sales and viability of the development.

To return to an earlier point, it must be remembered that when using TIA as the measurement of imperviousness, the predicted changes in runoff due to increasing imperviousness may be smaller (Brabec, Schulte & Richards 2002). This would usually be the case if the development would be built in the traditional fashion, with the stormwater management emphasis on moving the most amount of water away in the shortest time. Fortunately, this development is a pilot project for ecologically designed housing in the Helsinki region, and will showcase several techniques of Water-Sensitive Urban Design. Although EIA could not be determined for the area to be built, it can be assumed that due to these techniques, EIA will only increase by a few percentage points, rather than in proportion to or even approaching TIA as would occur under traditional stormwater management. For example, the estimated increase in TIA post-KUNTA for rooftops is 30%, however the development will build one large (approx.. 2000m^2) green roof on the community centre as well as several other small greenroofs. This will reduce the estimated increase in rooftop imperviousness significantly by disconnecting some of those surfaces.

Figure 36. Artists impression of central Kuninkaantammi development and greenroof on the community centre. Source: Suvi Tyynilä (2011), City of Helsinki.

Schueler (1994) reviewed eleven studies to determine classifications of urban streams based on their imperviousness, and the results of this study places Hakuninmaanoja in the ‘impacted’ stream category (TIA 11-25%). Streams under this category suffer from unstable channels and loss of diversity, and the key management objective is to prevent further degradation by retrofitting existing urban areas with WSUD and applying those techniques to new ones. This is set to occur under the KUNTA development, however the TIA of the catchment is still expected to increase to almost 30%. According to Schueler’s classifications this will degrade Hakuninmaanoja to the ‘non-supporting’ (TIA 26-100%) stream category. This category recognises that pre-development channel dimensions and biodiversity cannot be attained even with widespread application of WSUD. Here, the primary watershed management objective is to protect downstream water quality through pollutant removal (in this case, Mätäjoki). This is the purpose of the raingardens, stormwater detention ponds and greenroofs to be built as part of the development, which will serve to “stretch” the imperviousness-stream quality ratio so that EIA does not approach TIA, as occurs in sites with traditional stormwater management.

Based on these results, it is the contention of this paper that during coarse-scale or preliminary planning, the LUC method may be a quicker and easier determination of imperviousness in small urban catchments than field surveying EIA, and can also give a more complete picture of the runoff volumes to be expected from the whole catchment, including pervious as well as impervious areas. In the planning context this could be used as baseline data, and as a comparison to more accurate data as it becomes available. Moreover, as the runoff coefficients upon which the method is based are adapted for Finnish conditions, it can be considered even more appropriate, in addition to the much shorter time taken to get results (one to two days for LUC versus two months for field survey). However, when determining the locations and sizes of stormwater infrastructure within a planned development or existing urban area, especially concerning new buildings, EIA should be used to prevent underestimation of runoff volumes, which could lead to undersized BMPs and possible flooding problems. In lower density sub-catchments roads and driveways should be field surveyed as they may not display full connectivity, affecting the EIA percentage more than in small higher density sub-catchments.

The overall objective of sustainable urban water management should be to use preventative planning to minimise newly created imperviousness, and to keep the connectivity of that imperviousness to the lowest level necessary to prevent flooding issues. Specifically, this means incorporating into planning laws maximum allowable levels of total and effective imperviousness to be created in new developments, especially in regards to transport infrastructure. Watershed management plans (see Schueler & Holland (2000), *The Practice of Watershed Protection*) can help communities categorise their streams and develop unique management options for each, based on the current and projected imperviousness of the sub-catchments. This helps to establish limits to imperviousness creation and reduce the connectivity of those already existing, while implementing various techniques of Water Sensitive Urban Design to mitigate increased runoff flows and pollutant concentrations from the remaining impervious areas. There are also many non-structural methods of reducing the impact of stormwater runoff on streams, for example storm drain inlet stenciling, community and school education programs, and regular drain and BMP cleaning (US EPA 1999). This holistic treatment train will go a long way to minimising hydrologic and water quality disturbance of urban streams, and is a much more preferable situation to the many ‘non-decisions’ made regarding increased imperviousness every day in cities all over the world.

Fortunately there are many opportunities to reduce EIA and total imperviousness. Transport infrastructure exerts a disproportionate impact on streams because they comprise a larger area (approx.. 60% of TIA) and have a greater degree of connectivity than rooftops, especially in lower density areas, as the results of this study demonstrate. Road lengths are a function of urban density, so developing compact cities will naturally help to reduce those. For example, road length can be cut by 50-75% in cluster developments (Schueler 1994; US EPA 1999), as opposed to traditional cul-de-sac sprawl developments. However, road widths are often overlooked as another way to reduce imperviousness, and are often not as highly regulated as buildings in local zoning ordinances. Roads can be often much wider than they need to be, especially in modern sprawl developments where the car is king. Reducing road widths by 30cm can reduce total road surface area by 25-30% (Schueler 1994). Moreover, parking spaces are often oversupplied and can thus be reduced, having a flow-on benefit of promoting public transport and cycling. Parking lots can even be built using pervious paving, although some concern exists over their usefulness in cold climates. These techniques also lead to significant cost savings for developers in terms of area of road built, and for city administrations in terms of amount of stormwater infrastructure needed to cater for greater road lengths.

Figure 36. Example of rainwater collection barrels underneath rooftop downpipes in Hakuninmaanoja catchment.

In the Finnish context, there are several excellent examples of where EIA is already being minimised, and which are a part of the local culture, though they are under threat because of planning laws. The Hakuninmaanoja catchment is likely no exception in terms of the general characteristics of Finnish suburbs, where many older buildings are not connected to the public stormwater system. While most buildings still have downpipes connecting the rooftop to the ground surface, barrels that collect the rainwater during the warmer months (often for garden use) are placed underneath them (Fig. 36).

While some barrels are in place because there are no underground drainage connections, others are placed even though there are drainage connections to the city stormwater infrastructure. Other residents have rigged their downpipes to drain to the lawn rather than continue to underground stormwater pipes (Fig. 37).

A further type of rooftop disconnection is to use onsite infiltration systems (imeytyskenttä in Finnish) to deal with rooftop runoff, and often greywater as well. Rainwater is directed to a sand and gravel pollution filtration system underground, where over time it travels into groundwater or nearby streams. This system is known to be in place in several properties in Hakuninmaanoja catchment, although total numbers are unknown. Properties using this kind of system must be careful regarding soil type, as clay and rocky soils may be unsuitable and could lead to flooding.

Figure 37. Example of home-made rooftop disconnection in Hakuninmaanoja catchment.

While these local rooftop disconnection techniques are problematic for field surveying EIA, it is a very positive sign that many suburban people understand and care about water, as it would be much easier to simply 'connect and forget'. It allows smaller rain events to be infiltrated rather than contributing to surface runoff and adding to stream channel instability. Newer buildings in the catchment were almost universally connected to the stormwater system (though there are no figures to support this visual observation), a result also seen in the United States (Roy & Shuster 2009). This may be due to the current planning law of the City of Helsinki, which mandated in 2011 that all houses in the area were to be connected to the stormwater system within a year (as told to the researcher by residents during the field survey). This is unfortunate as rooftop disconnection is one of the primary ways to reduce EIA in low to medium density catchments where there is space to infiltrate the water, or reuse it on gardens. This policy will have to be rethought if reducing EIA and maintaining streams at ‘sensitive’ or ‘impacted’ levels is a continuing priority. Moreover, the City of Helsinki should actively engage communities to promote these types of systems on a wider scale, especially considering future developments will add to the runoff volumes already occurring. A sensible approach to reducing imperviousness is through economic incentives, for example in the City of Vaasa, Finland, where homeowners are charged for municipal stormwater fees on the basis of how much imperviousness occurs on their lot (Vaasanvesi [Vaasa Water] 2006).

As urban density increases, rooftop disconnection without application of WSUD becomes problematic, as the water can then create flooding problems. At this stage, a suite of techniques becomes viable, such as bioswales, raingardens, green roofs and pervious pavements. The KUNTA development will implement at least the first three, although the cold climate in Finland means some adjustments to standard designs are necessary, including depth and type of infiltration media, and plant composition and density. The raingardens to be built in KUNTA will be located off-street, within semi-enclosed courtyards of apartment buildings (Fig. 38). This will help to isolate them from direct deposition of transport emissions, although some fraction will be expected. De-icing chemicals and salt should also not be an issue for these raingardens for the same reason. Rooftops often contain high levels of copper and zinc, which are reported to have high removal rates by raingardens (Weiss, Hondzo & Semmens 2006; Muthanna *et al.* 2007a; Li & Davis 2009). Frozen media and reduced biological activity may be an issue however, and should be studied once the development has been built to assess their usefulness in later housing developments in the Helsinki region. Moreover, plant composition and density will be important – the right balance of high-accumulation of pollutants, hardiness for the northern climate and aesthetic qualities will be needed. Research indicates that in raingardens most pollutant removal takes place in the mulch layer between plant tissue and the soil layer (Muthanna *et al.* 2007; 2007a). A plan for the removal of this layer will need to be developed by the City of Helsinki and private investors if the usefulness of the raingardens is to be maintained, with biannual maintenance or more needed to

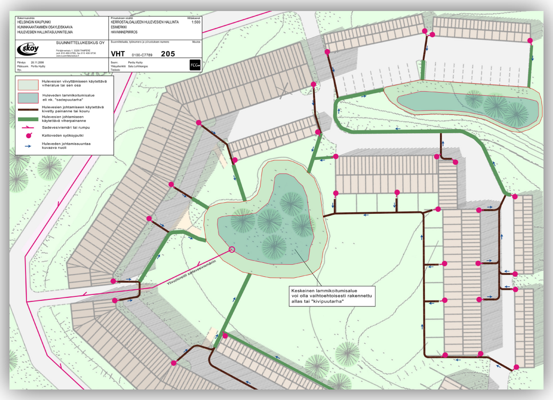


Figure 38. Example of raingardens in KUNTA plans. Source: Suunnittelukeskus OY (2007).

replace mulch, remove sediment and replace dead or diseased vegetation (US EPA 1999). It must be remembered that stormwater management BMPs are pollutant collection devices, and will not function biologically as well as natural vegetation.

While many studies are optimistic about the cold climate performance of raingardens in heavy metals (Heyvaert, Reuter & Goldman 2006; Dietz 2007; Muthanna *et al.* 2007; Roseen *et al.* 2009), phosphorus and suspended solids removal (Blecken *et al.* 2010), some concerns exist regarding the winter potential for peak flow reduction (particularly of rain on snow and related spring thaw events) and nitrogen and hydrocarbons removal (Dietz 2007; Blecken *et al.* 2010). For example, ice can form on top of the mulch layer and force incoming water to flow straight out of the raingarden (Muthanna, Viklander & Thorolfsson 2008). These should be the subject of further study after KUNTA has been built, and will help inform later developments.

Vegetated bioswales will be located along the edges of main roads in the KUNTA development (Fig. 39), replacing the traditional curb-and-gutter drainage systems, and will direct roadside runoff towards the stormwater detention ponds. Swales are vegetated and recessed areas designed to attenuate stormwater runoff and infiltrate certain categories of pollutants, particularly sediments. They are a useful option in cold climates because they do not pond water for long periods, reducing the warming effect on cold water streams. However, they are best located in flatter (slope 1-2°) areas with permeable soils, to maximise infiltration (US EPA 2010). In the KUNTA area this is not the case, where most slopes are 4° or greater, and soils are mostly clay or rock. In the climate of southern Finland they will be subject to winter conditions, with a consequent problem of high sand and salt input from winter road maintenance. These swales will most likely also be used for snow storage during the winter, so the choice of plants must include species with high salt, metals and hydrocarbon tolerance. The effectiveness of these swales should be studied after build-out to establish performance under these conditions.

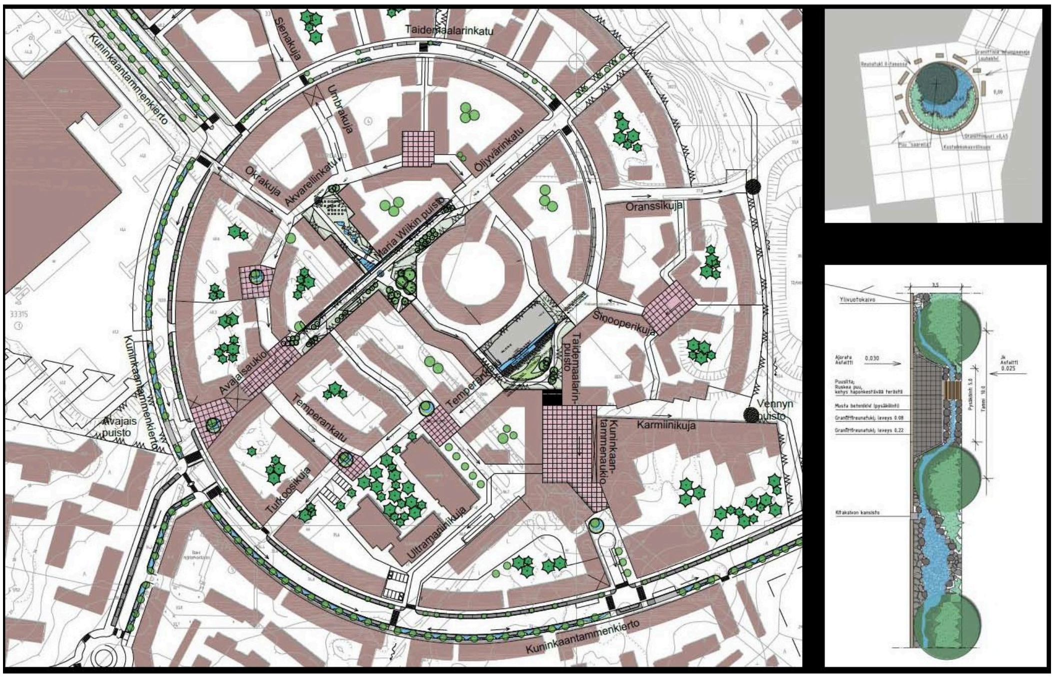


Figure 39. Plan of the central section of the KUNTA development, showing location of roadside swales, and their technical plans (right). Source: Suvi Tyynilä (2011), City of Helsinki.

As mentioned earlier, the three large stormwater detention ponds that will form Helene Schjerfbeck Park will take the remainder of runoff from the KUNTA area that has not infiltrated into the soil through the raingardens and roadside bioswales, and will be important when large storms overwhelm the capacity of onsite infiltration. Detention ponds (or wet ponds) maintain some depth of water throughout the year, and their primary function is to slow the movement of stormwater to receiving streams (helping to maintain a more natural hydrograph), as well as pollutant removal via settling. They are especially useful in removing sediments, nutrients and metals from runoff (Weiss, Hondzo & Semmons 2006), and satisfactory, though reduced performance has been seen in winter conditions (Heyvaert, Reuter & Goldman 2006). Aside from the potential thermal impact of warmer water from the detention ponds on Hakuninmaanoja, newly created ponds need from one to five years for the soil to stabilise and vegetation to grow large enough to effect pollutant removal (Heyvaert, Reuter & Goldman 2006). During this time the concentrations of various pollutants in Hakuninmaanoja will be likely to increase as a result of the development. This will also be an issue during construction of the urban area of KUNTA, during which time some control structures will be absolutely necessary to minimise sediment release from the construction site downstream.

4.1. Suggestions for further study

Linking stream quality and runoff quantity with land use and imperviousness is a difficult task, and requires a number of parameters which were unable to be measured in this study. Local measurements of rainfall and discharge are critical to this equation. The full picture of the effect of imperviousness on Hakuninmaanoja would become clearer if habitat and biotic measurements were gathered, as well as basic channel morphology data. Continued monitoring, especially during the construction phase and of the stormwater management BMPs to be built in KUNTA will be crucial to developing a further understanding of the right techniques to apply to Finnish environmental conditions, and importantly, which will be accepted by the residents of those future developments. Although EIA is currently the best way to correlate imperviousness with water quality, other measurements such as unpaved/paved road density, onsite infiltration system density, and socioeconomic data can also help to make imperviousness-stream quality relationships clearer.

5. Conclusion

The purpose of this project was to determine what the water quality of Hakuninmaanoja is currently, and estimate what it is likely to be in the future, through an accurate measurement of catchment imperviousness and the connectivity of that impervious area. Although comparison with undeveloped data for this stream cannot be made, the "urban stream syndrome" is already evident in this catchment of 15% Effective Impervious Area. Large temperature fluctuations, sediment input and peak flows are particular problems in this catchment. Phosphorus and nitrogen input would need further study due to sampling and analysis problems during this research. The increasing connectivity of the catchment due to planning decisions is also problematic for the future. The catchment is expected to move from low to medium density following the build-out of the Kuninkaantammi development beginning in 2013, which will increase Total Impervious Area to 30%. However, the Water Sensitive Urban Design planned for this 'eco development' pilot project will very likely mitigate the increase in Effective Impervious Area quite significantly. This will be to the benefit of the water quality and quantity issues in Hakuninmaanoja, and will reduce the impact of increasing urban density on this stream.

Under 'business as usual' situations streams will likely become 'non-supporting' in the face of increasing drainage density, which is often worse for biota than simple drainage ditches (Walsh *et. al.* 2001). Reducing EIA through preventative planning, watershed-based zoning and utilisation of the full suite of WSUD techniques can allow highly urban streams to be brought back from 'non-supporting' to 'impacted', and 'impacted' to 'sensitive', allowing a greater variety of management options to further improve recreational use, channel stability and water quality. This pilot project is therefore a step in the right direction towards the vision of a compact, medium to high density city with a TIA of up to or even greater than 50%, but with an EIA of 20% or less. Compact cities have received much attention in the literature and in public media in recent years, but unless EIA is reduced as part of a holistic stormwater treatment train that utilises the full range of WSUD techniques, such high density will lead to impaired local waterways.

In the context of stormwater management, the central problem to human life in cities is that we need to create impervious surfaces to shelter us and to transport us from our homes to our jobs and to our sites of leisure. The creation of that imperviousness leads to local deterioration of the environment as a result of the concentration of our activities in small areas. Consequently, if we want to reduce our impact on the local environment, impervious cover must be reduced, at the same time as implementing a full treatment train for stormwater quantity and quality problems, including non-structural techniques as covered in this paper. Fortunately there are many avenues to reduce impervious cover in existing and new developments. Moreover, if we reduce the connectedness of those impervious surfaces that cannot be removed or prevented, we allow water to return to its normal processes of infiltration and evaporation. The philosophy should be of working with water, rather than against it. Overall, Hakuninmaanoja stands to benefit from the KUNTA development in ways that many urban streams are not so lucky to receive.

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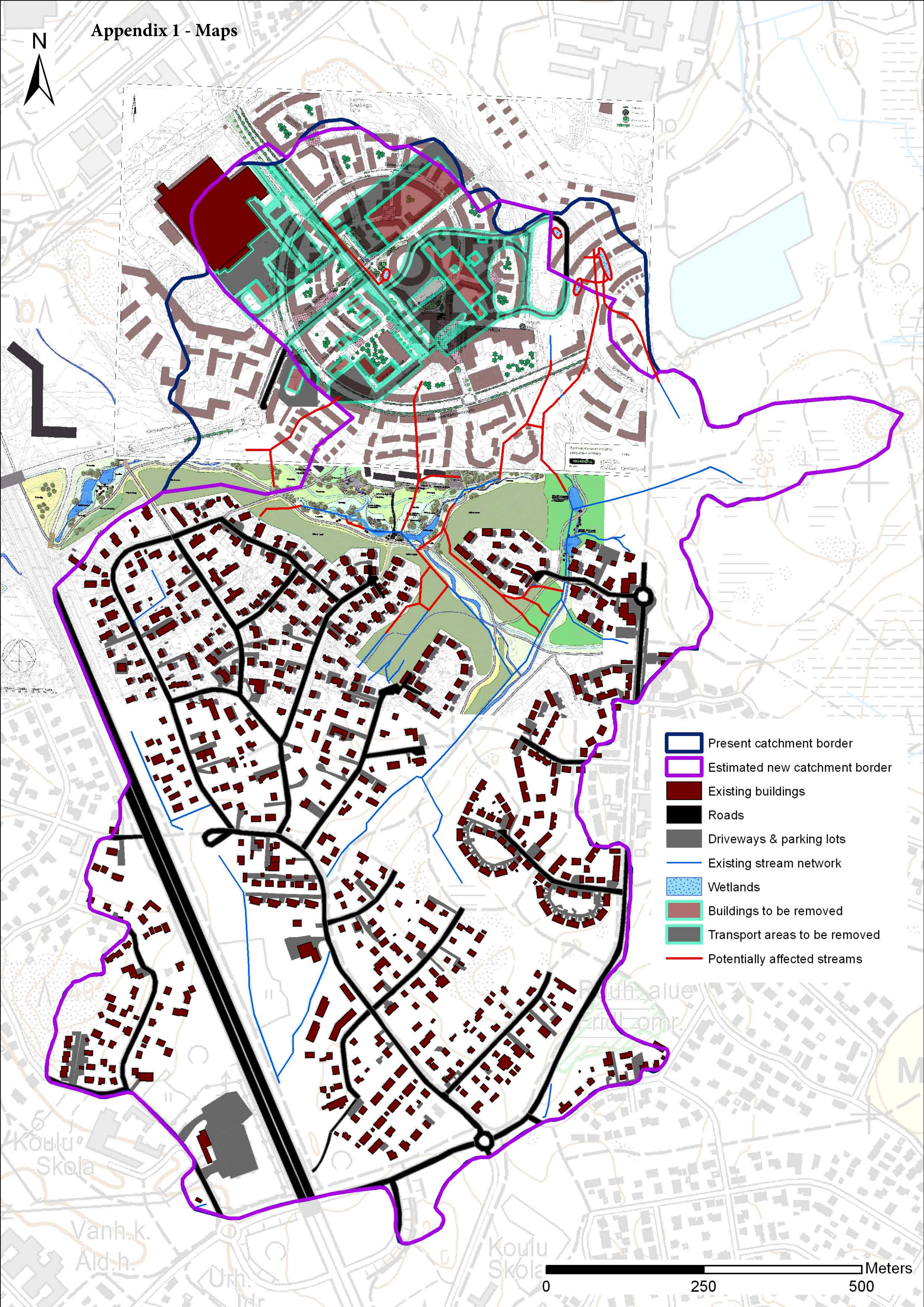
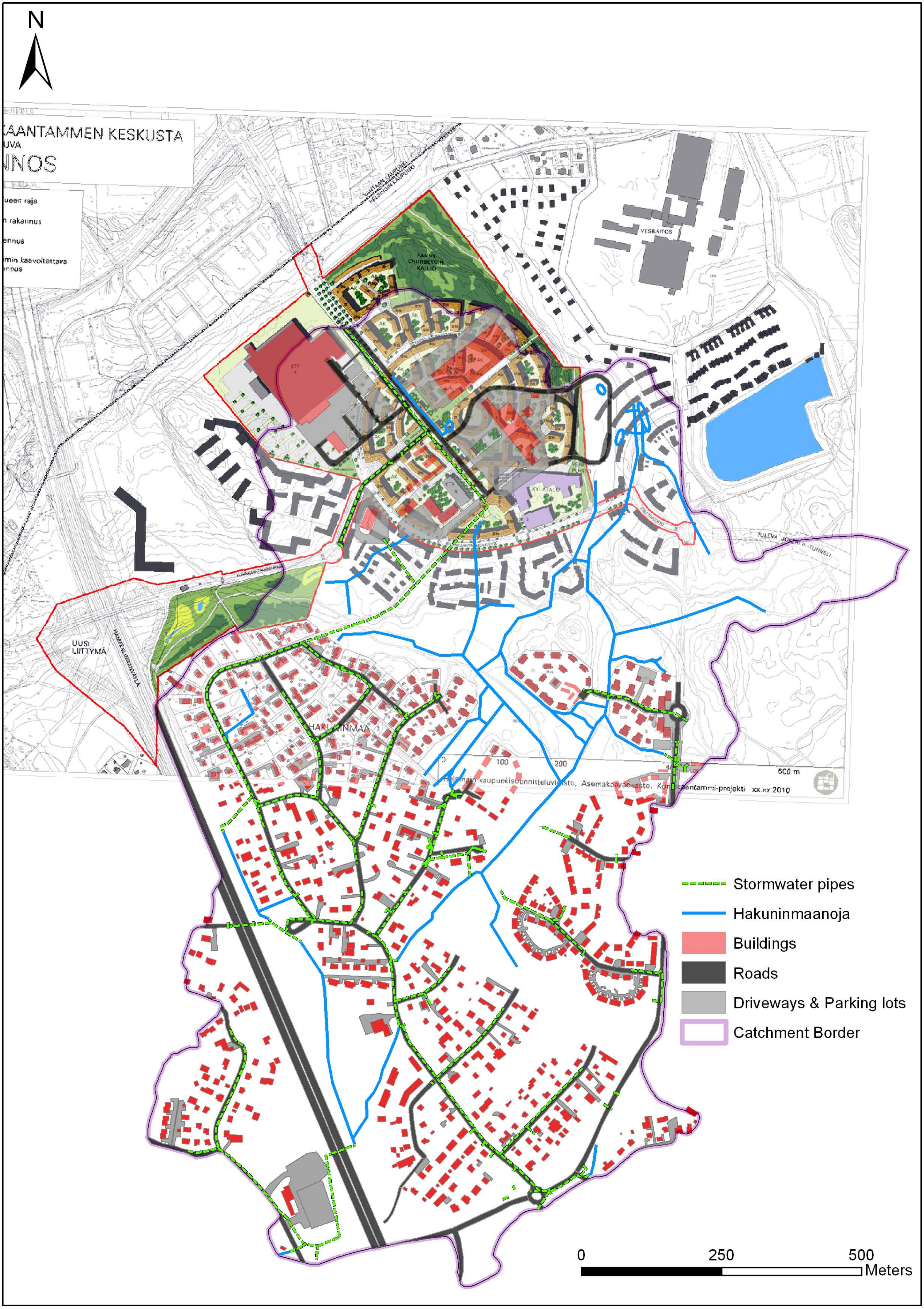
Appendices

Appendix 1 - Maps

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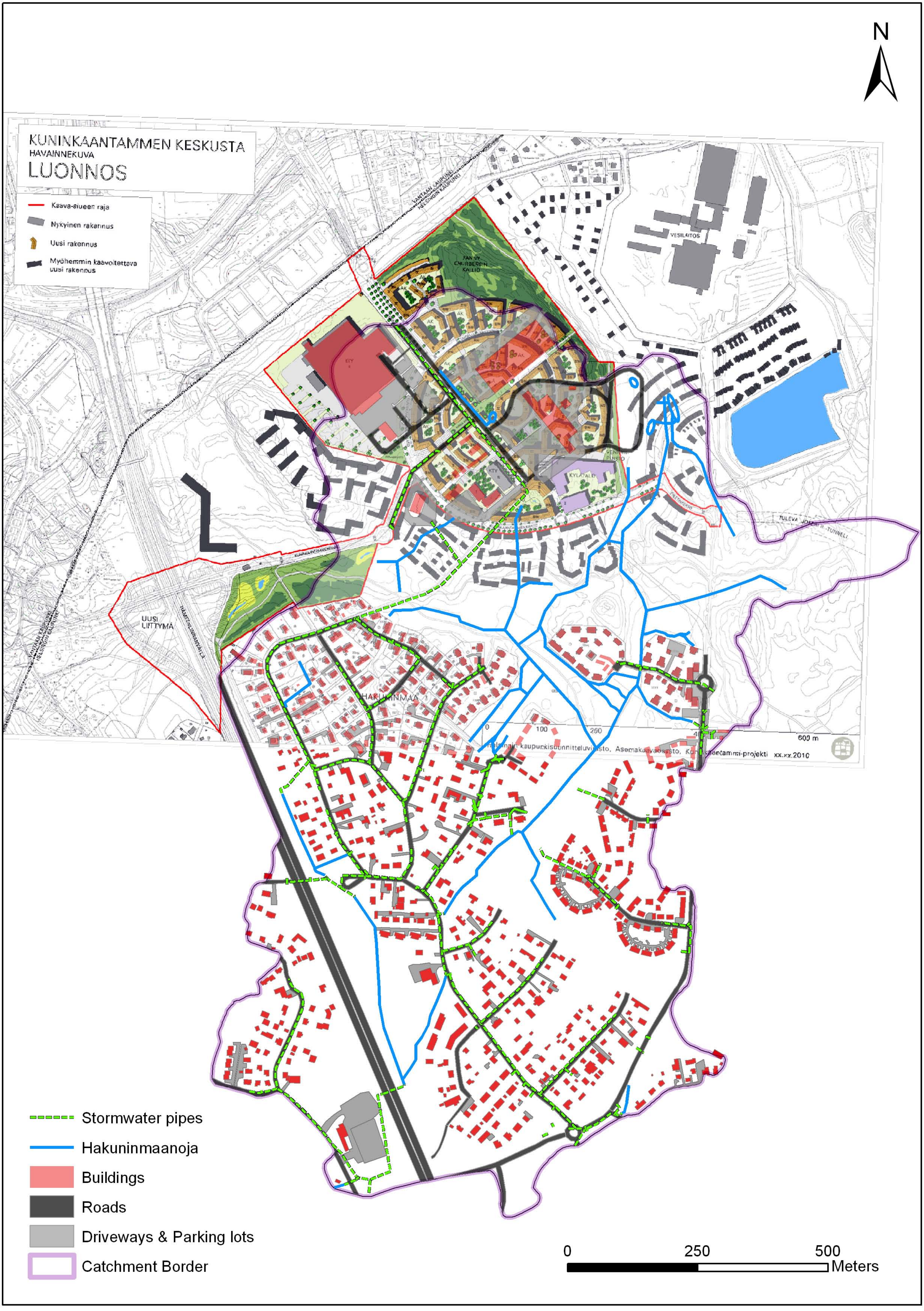
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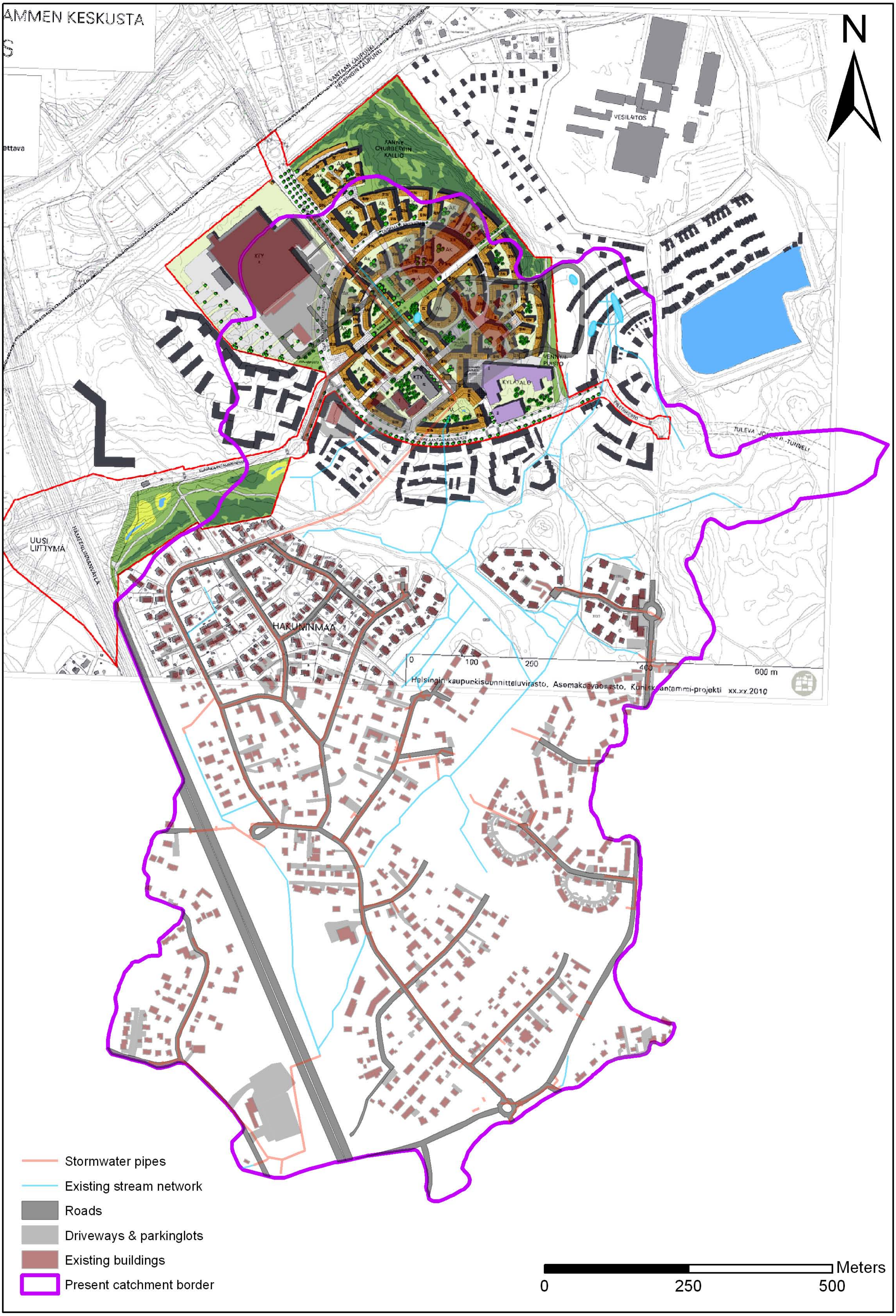

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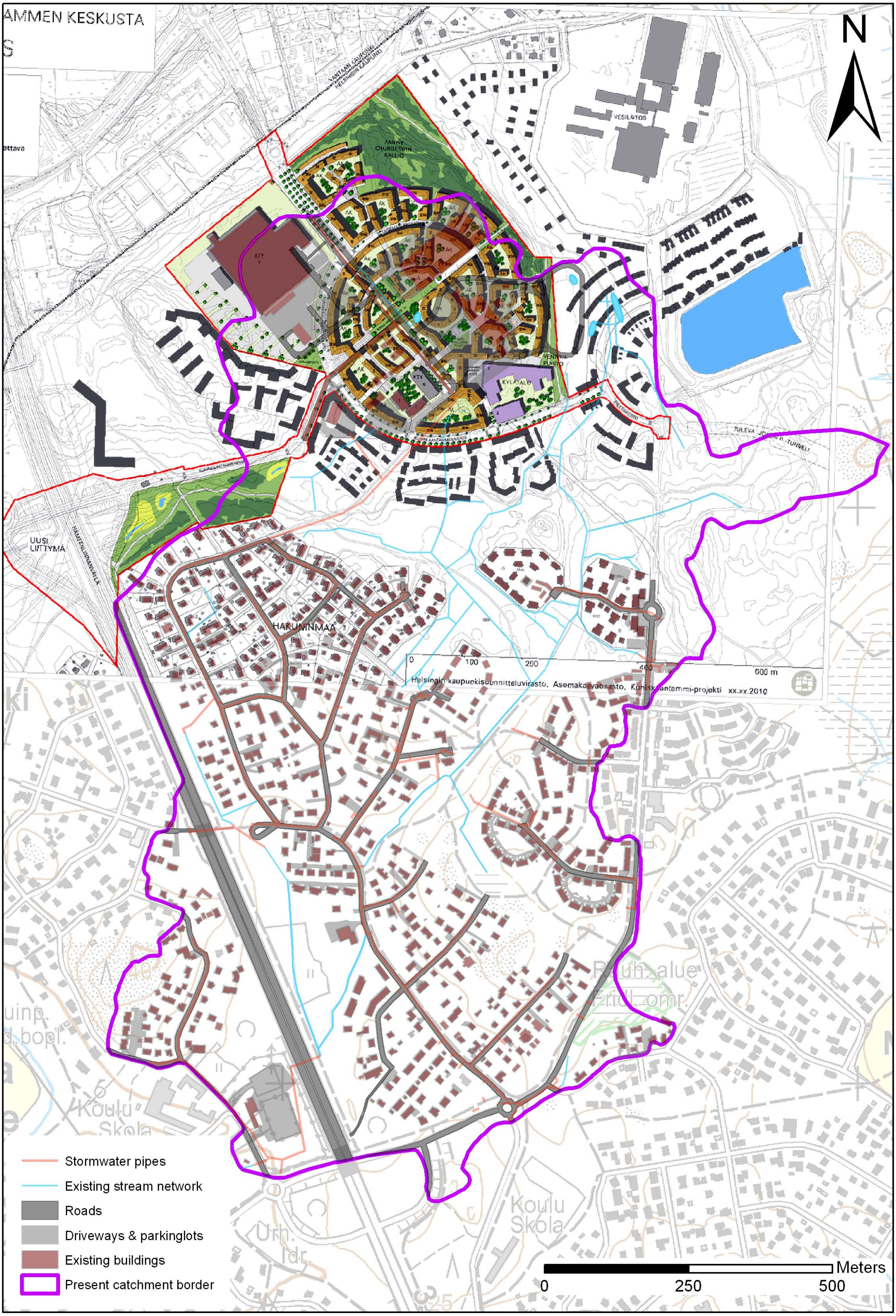
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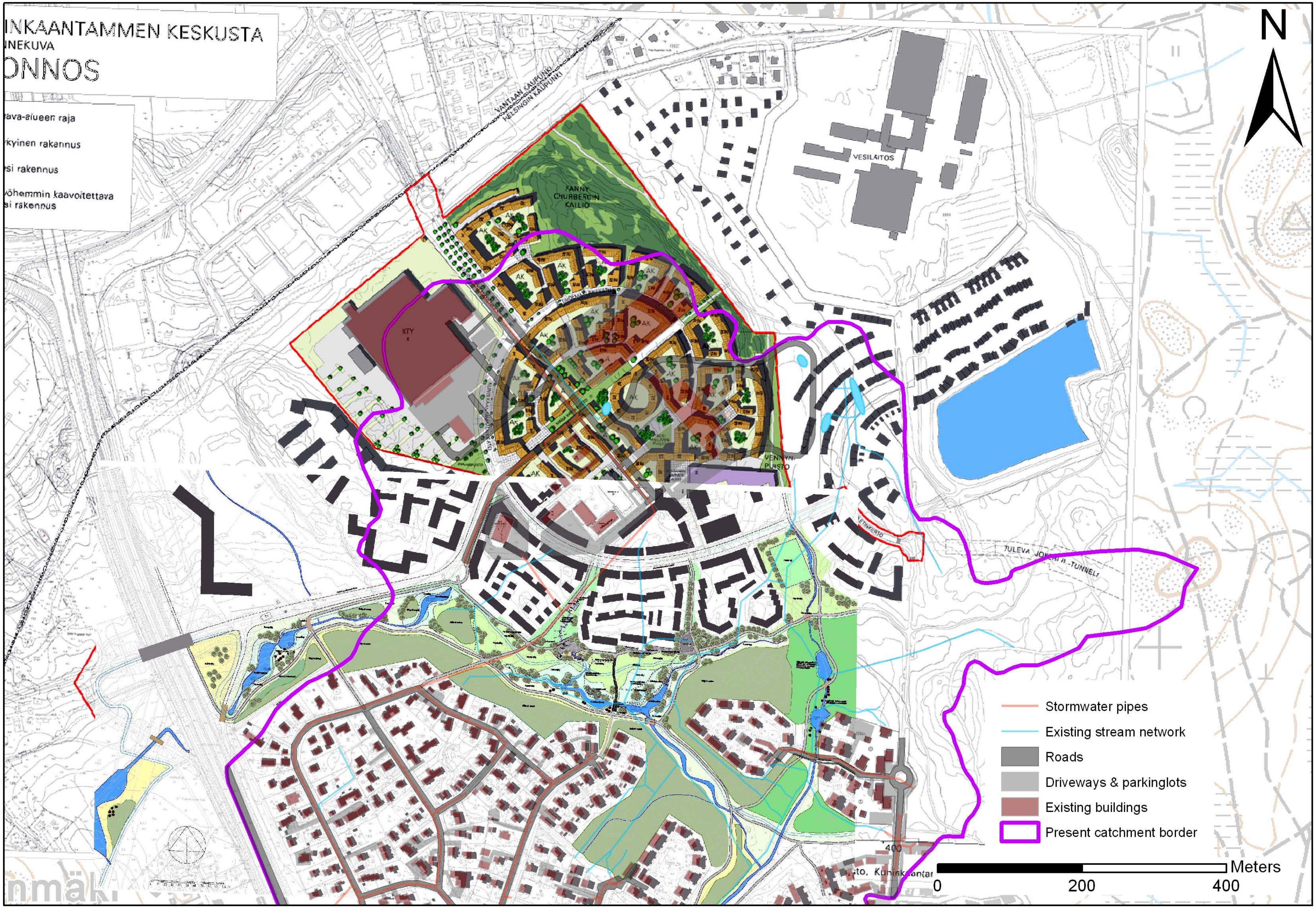

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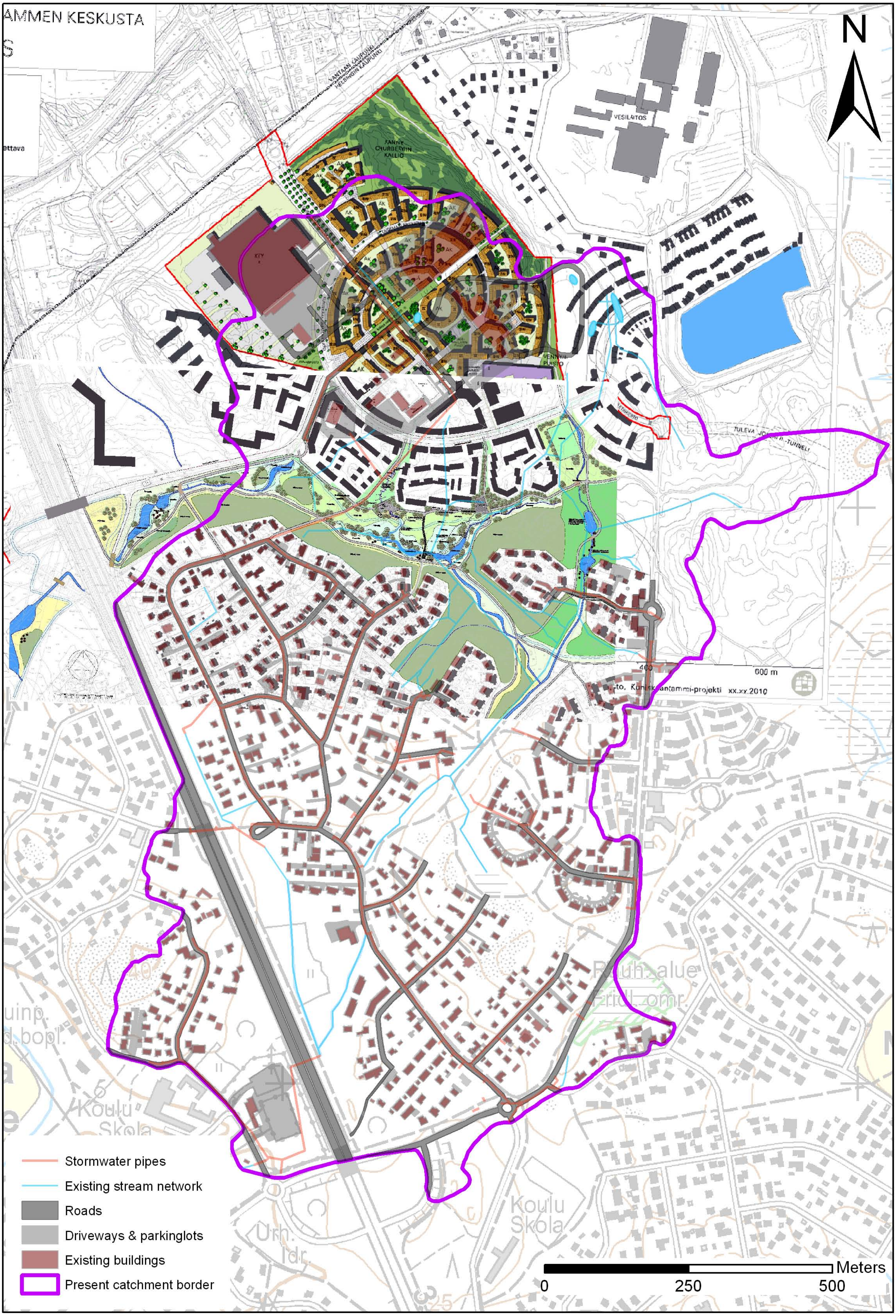
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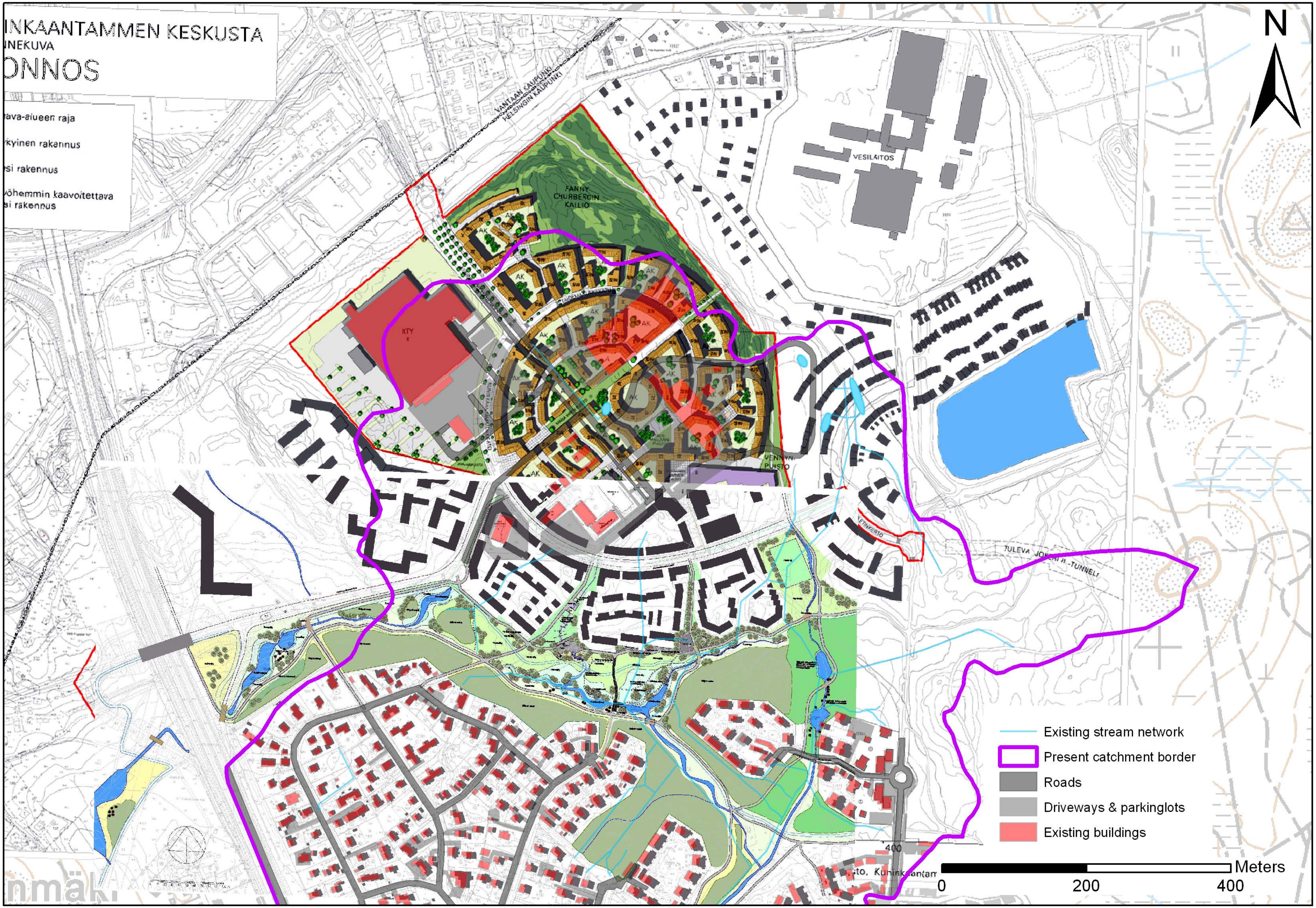

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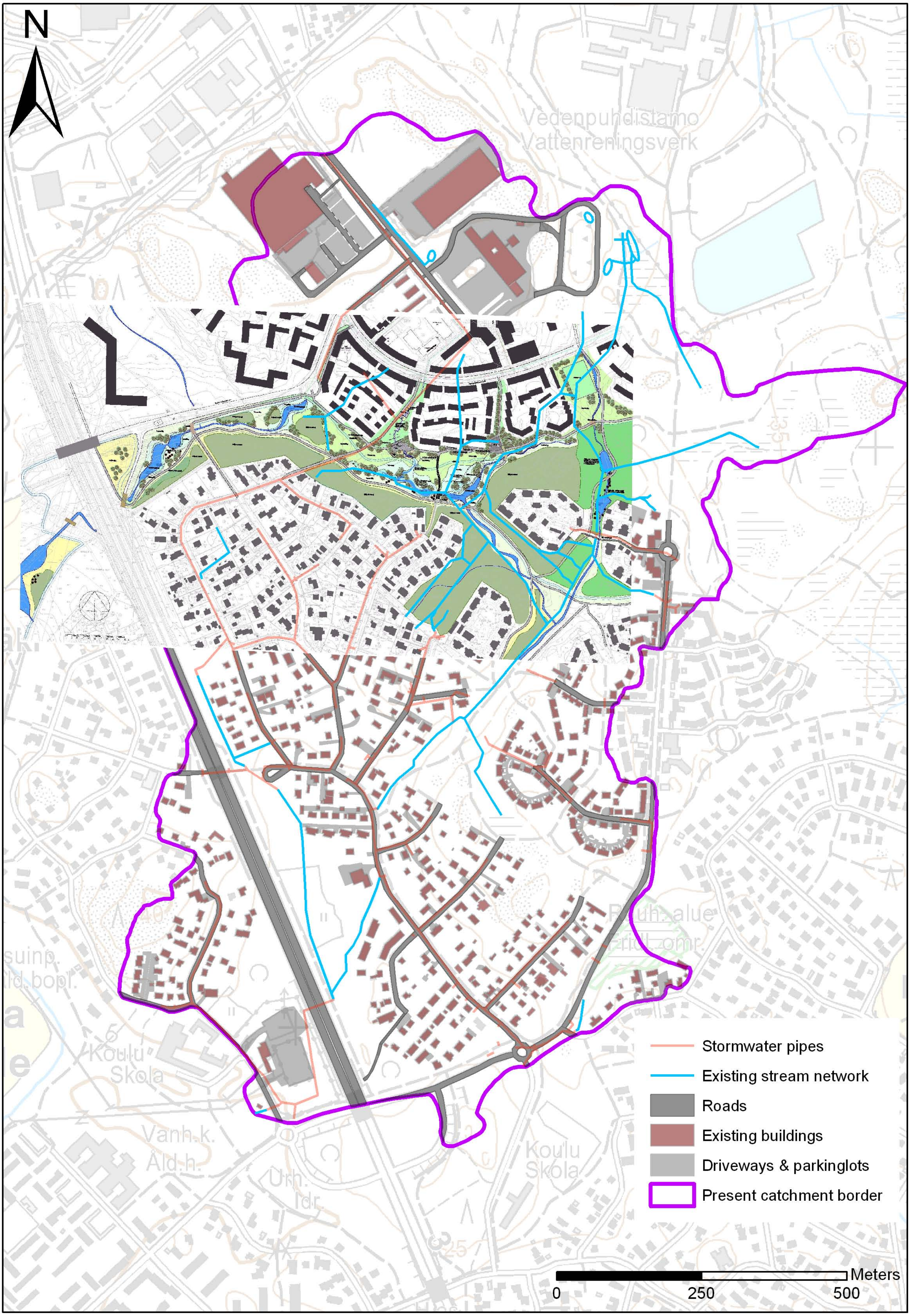
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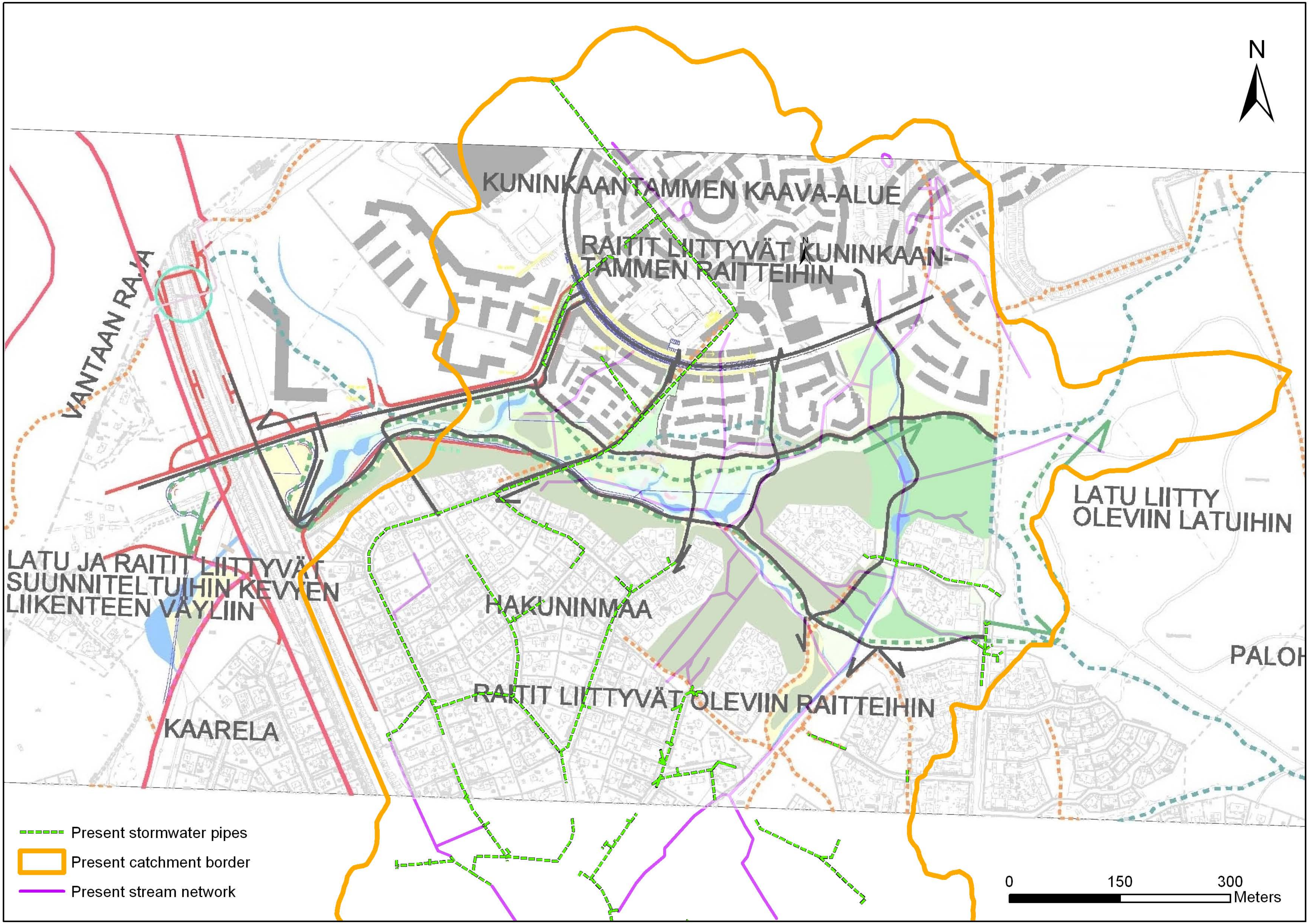
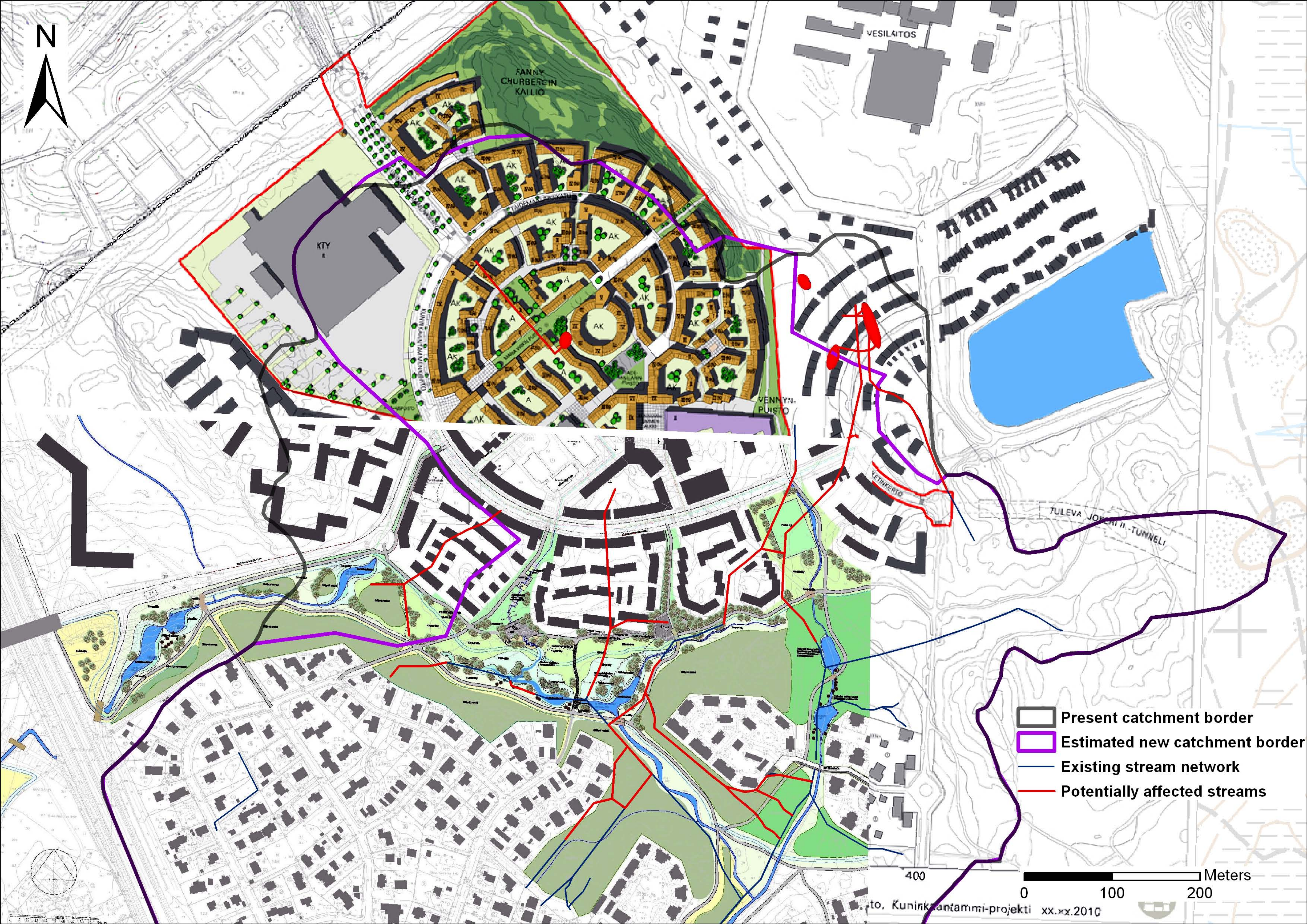
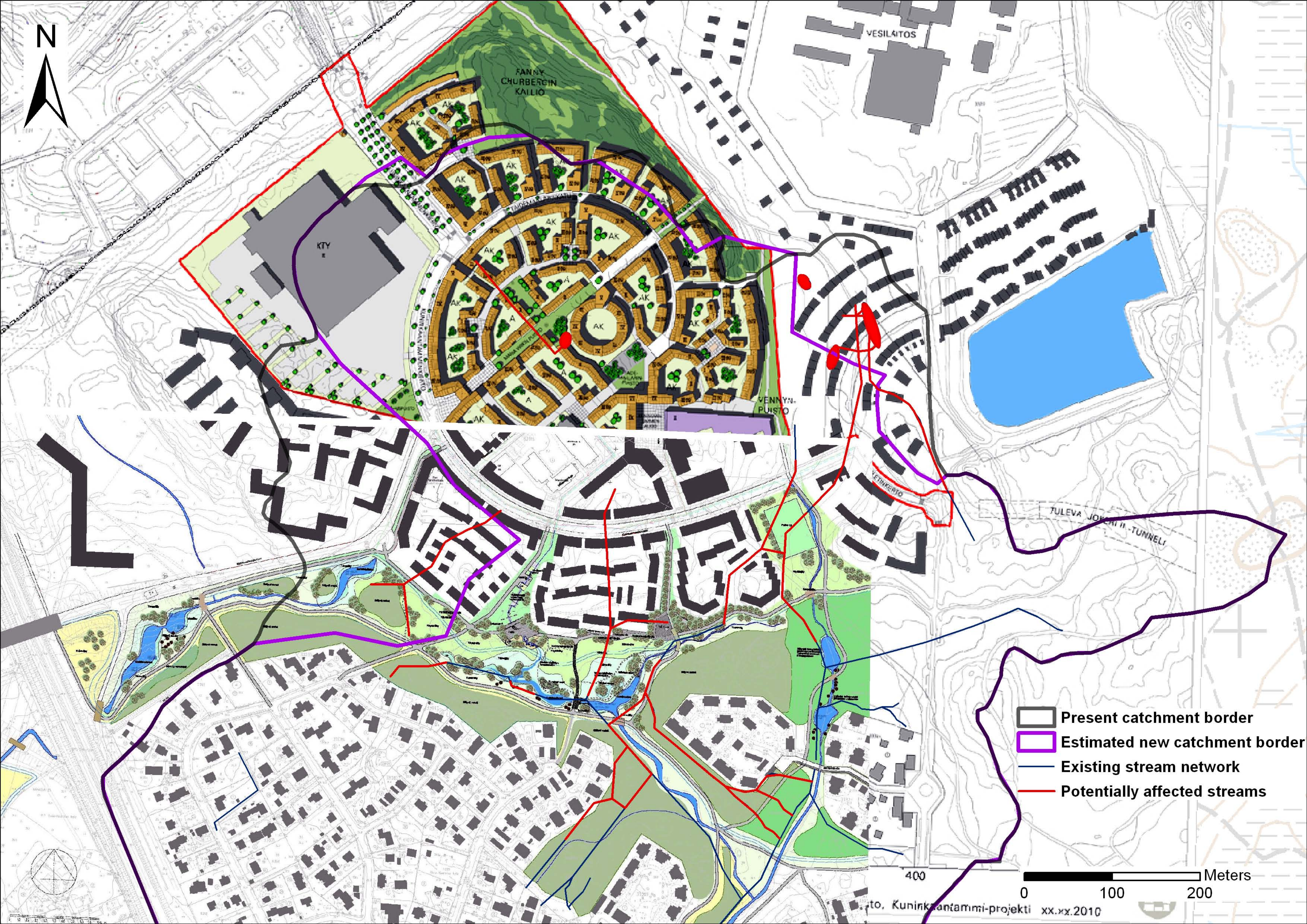
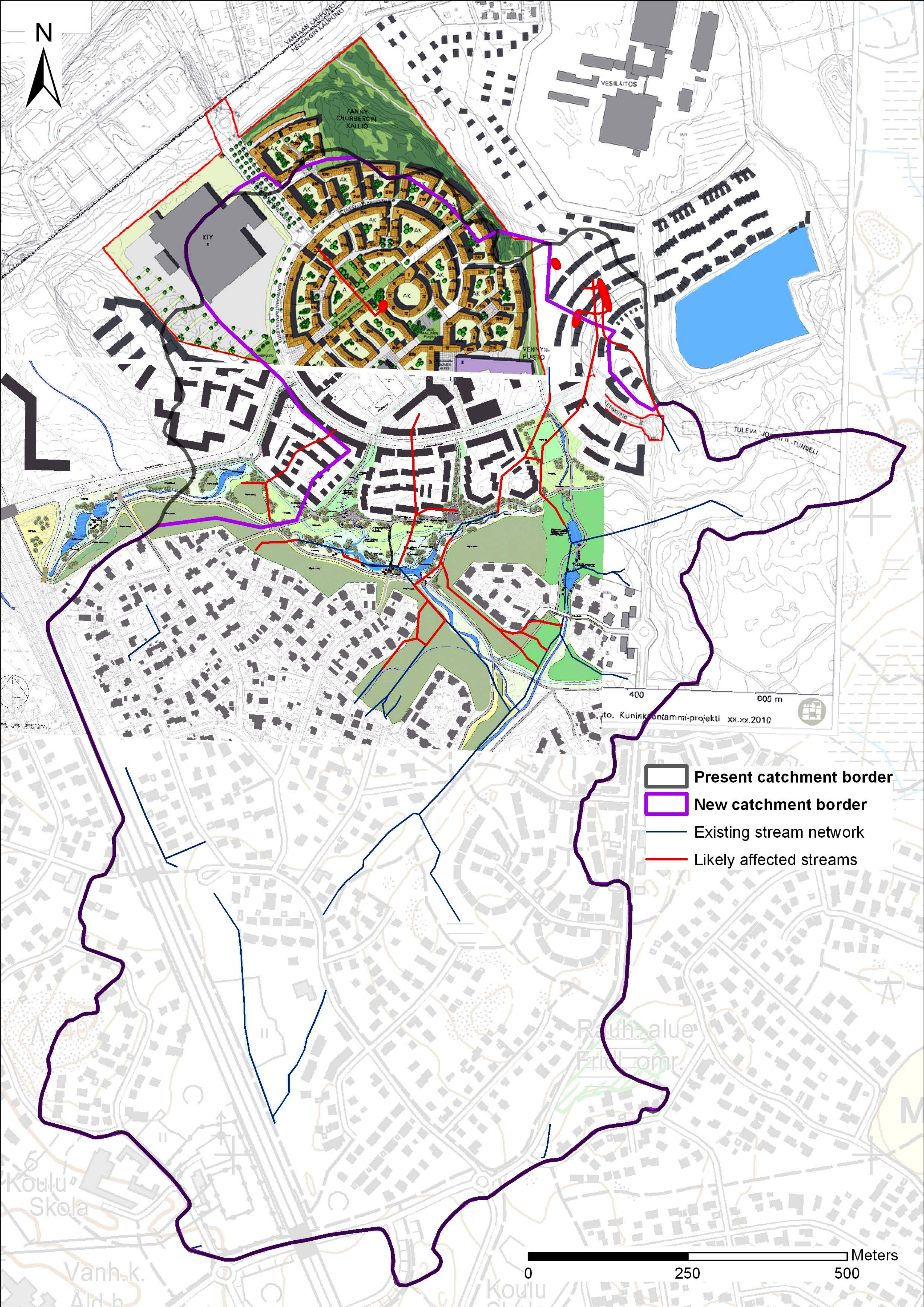
Åld.h.
Urh.
Idr.
Koulu
Skola
Stormwater pipes
Existing stream network
Roads
Existing buildings
Driveways & parkinglots
Present catchment border
Meters
0
250
500


N
KUNINKAANTAMMEN KAAVA-ALUE
RAITIT LIITTYVÄT KUNINKAAN-TAMMEN RAITTEIHIN
VANTAAN RAJA
LATU LIITTY OLEVIIN LATUIHIN
LATU JA RAITIT LIITTYVÄT SUUNNITELTUIHIN KEVYEN LIIKENTEEN VÄYLIIN
HAKUNINMAA
PALOH
RAITIT LIITTYVÄT OLEVIIN RAITTEIHIN
KAARELA
Present stormwater pipes
Present catchment border
Present stream network
0
150
300
Meters

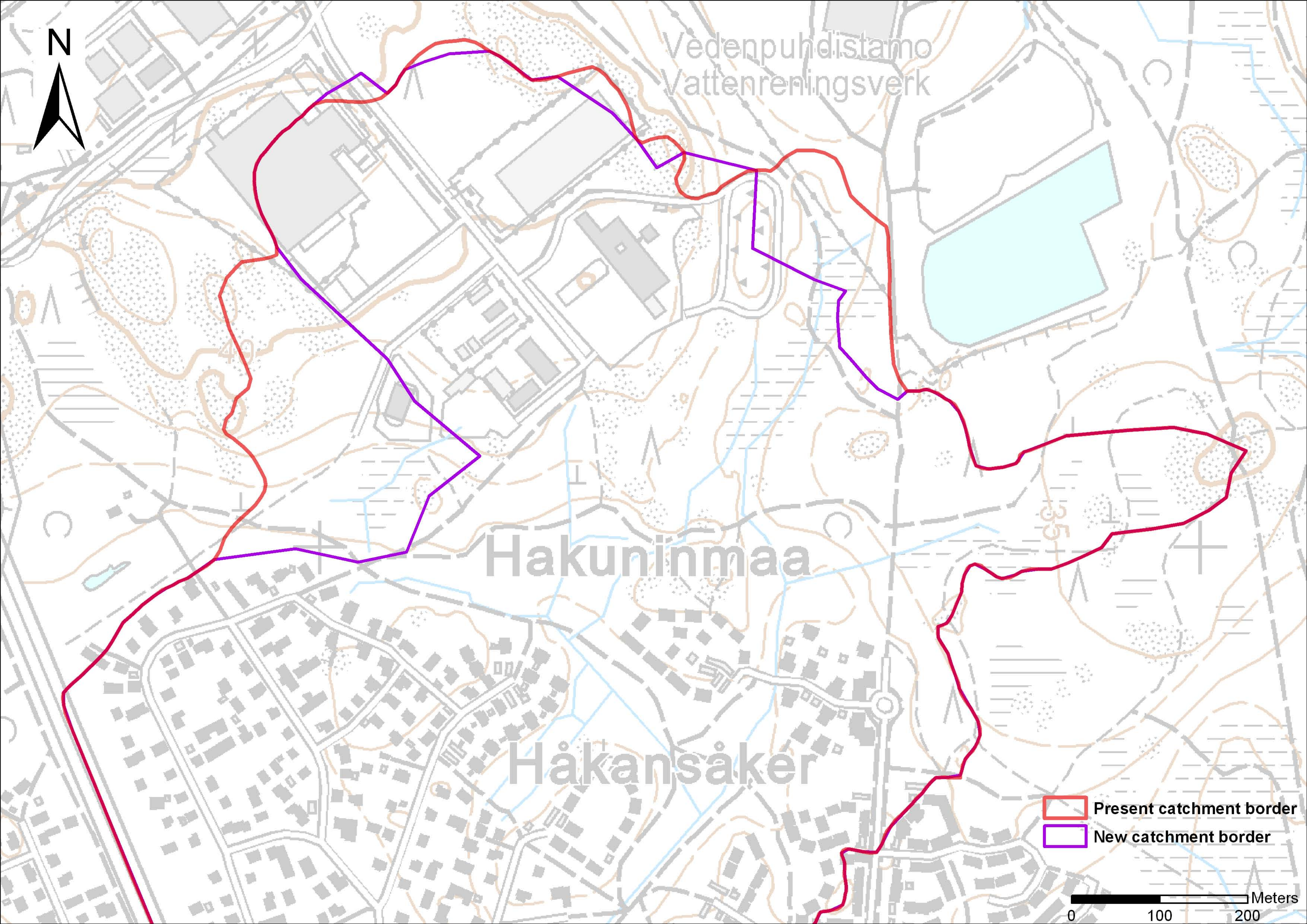
Kaava-alueen raja
Nykyinen rakennus
Uusi rakennus
Myöhemmin kaavoitettava uusi rakennus
N
VESILAITOS
FANNY CHURBERGIN KALLIO
AK
KTY
KYLÄTALO
UUSI LIITTYMÄ
HAKUNINMAA
TULEVA JOKERI II -TUNNELI
0
100
200
600 m
Helsingin kaupunkisuunnitteluvirasto, Asemakaavaosasto, Kuninkaantammi-projekti xx.xx.2010
Stormwater pipes
Hakuninmaanoja
Buildings
Roads
Driveways & Parking lots
Catchment Border
0
150
300
Meters


N
VESILAITOS
FANNY CHURBERGIN KALLIO
KTY
AK
VENNYN-PUISTO
TULEVA JOKENIITUNNELI
Present catchment border
Estimated new catchment border
Existing stream network
Potentially affected streams
Meters
0
100
200
400
Kuninkaantammi-projekti xx.xx.2010

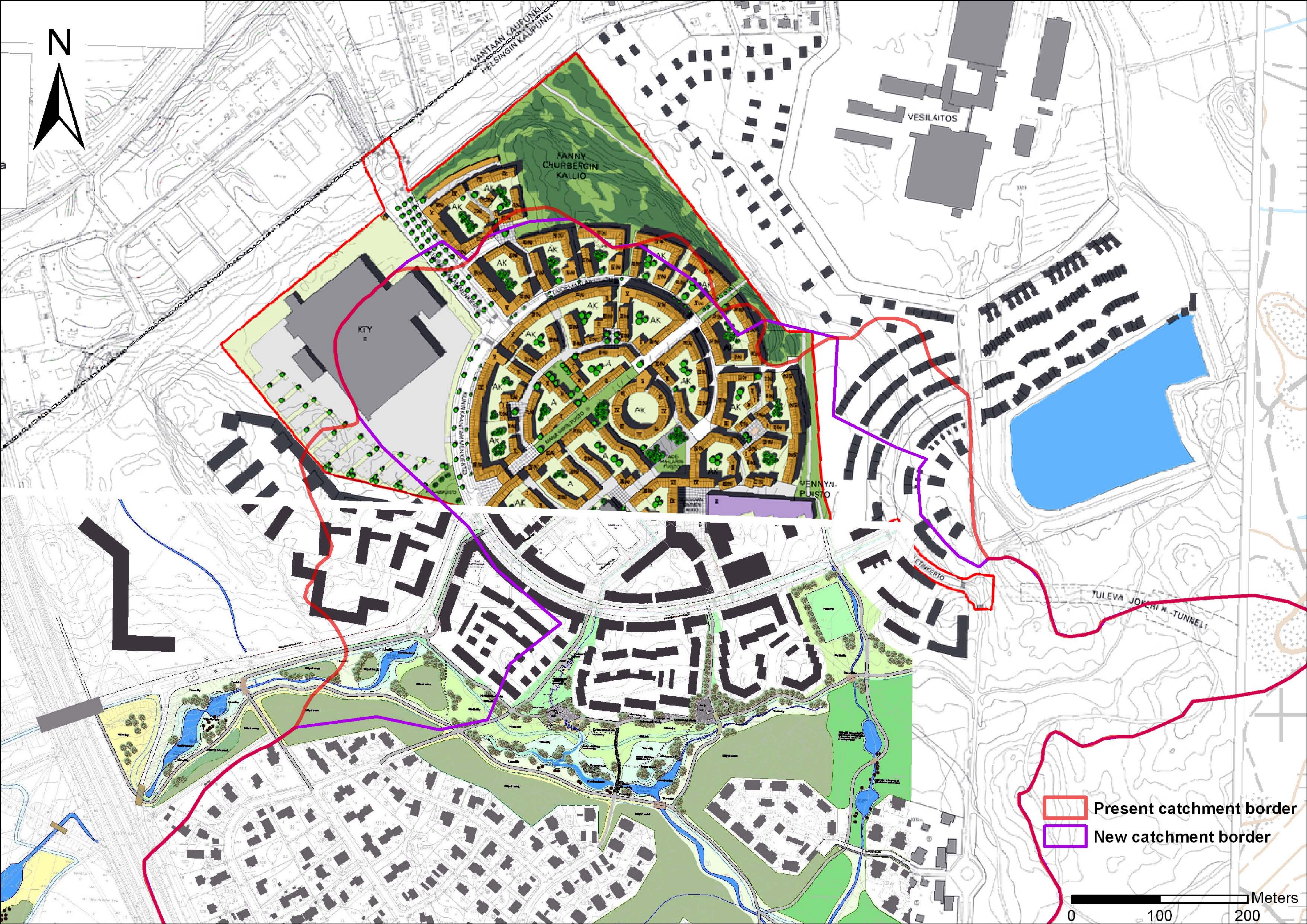

N
VESILAITOS
FANNY CHURBERGIN KALLIO
KTY
AK
VENNYN-PUISTO
TULEVA JOKERI II -TUNNELI
Present catchment border
Estimated new catchment border
Existing stream network
Potentially affected streams
400
0
100
200
Meters
Kuninkaantammi-projekti xx.xx.2010



N
Present catchment border
New catchment border
Existing stream network
Likely affected streams
0
250
500
Meters
VESILAITOS
FANNY CHURBERGIN KALLIO
VANTAAN KAUPUNKI
HELSINGIN KAUPUNKI
TULEVA
Koulu
Skola

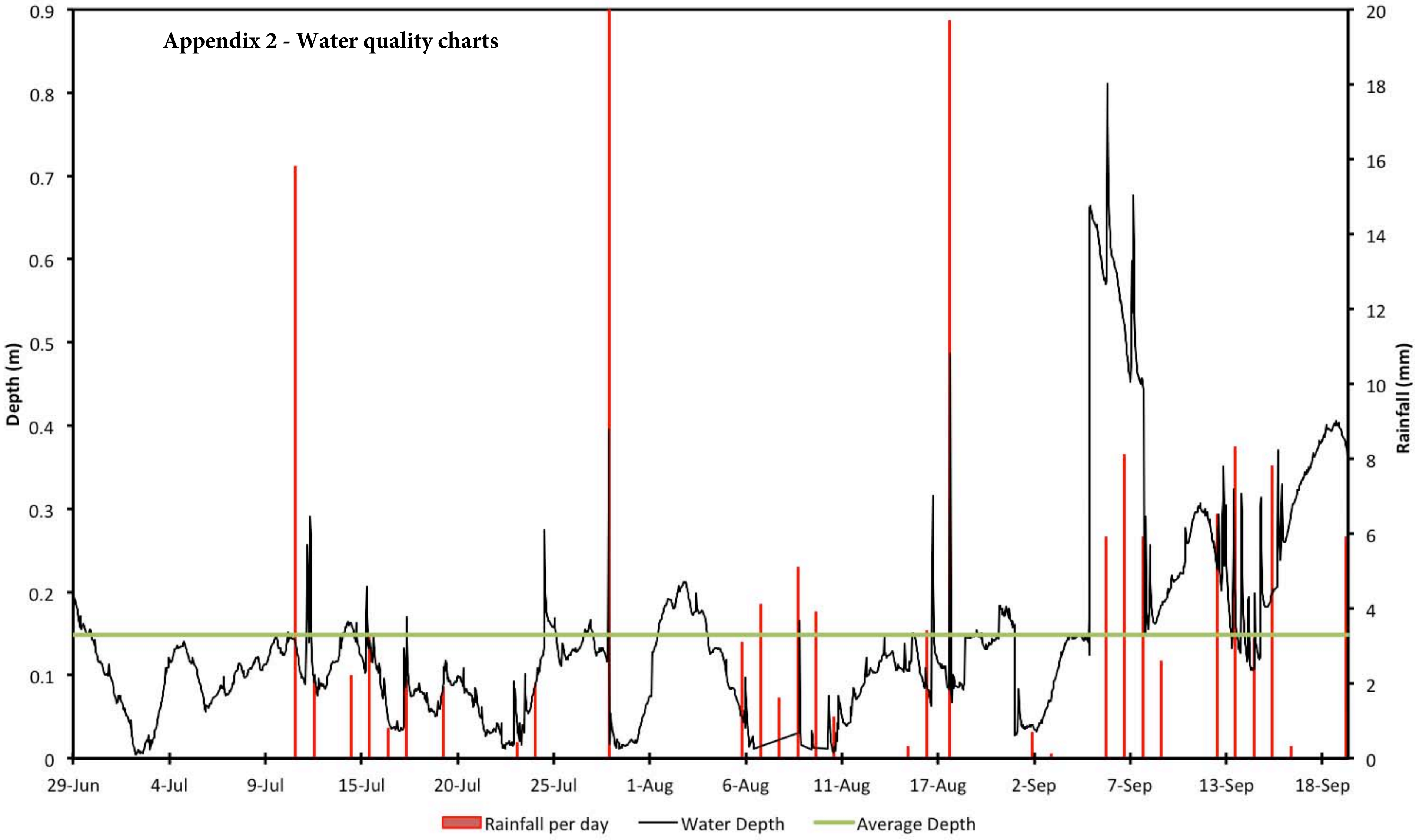


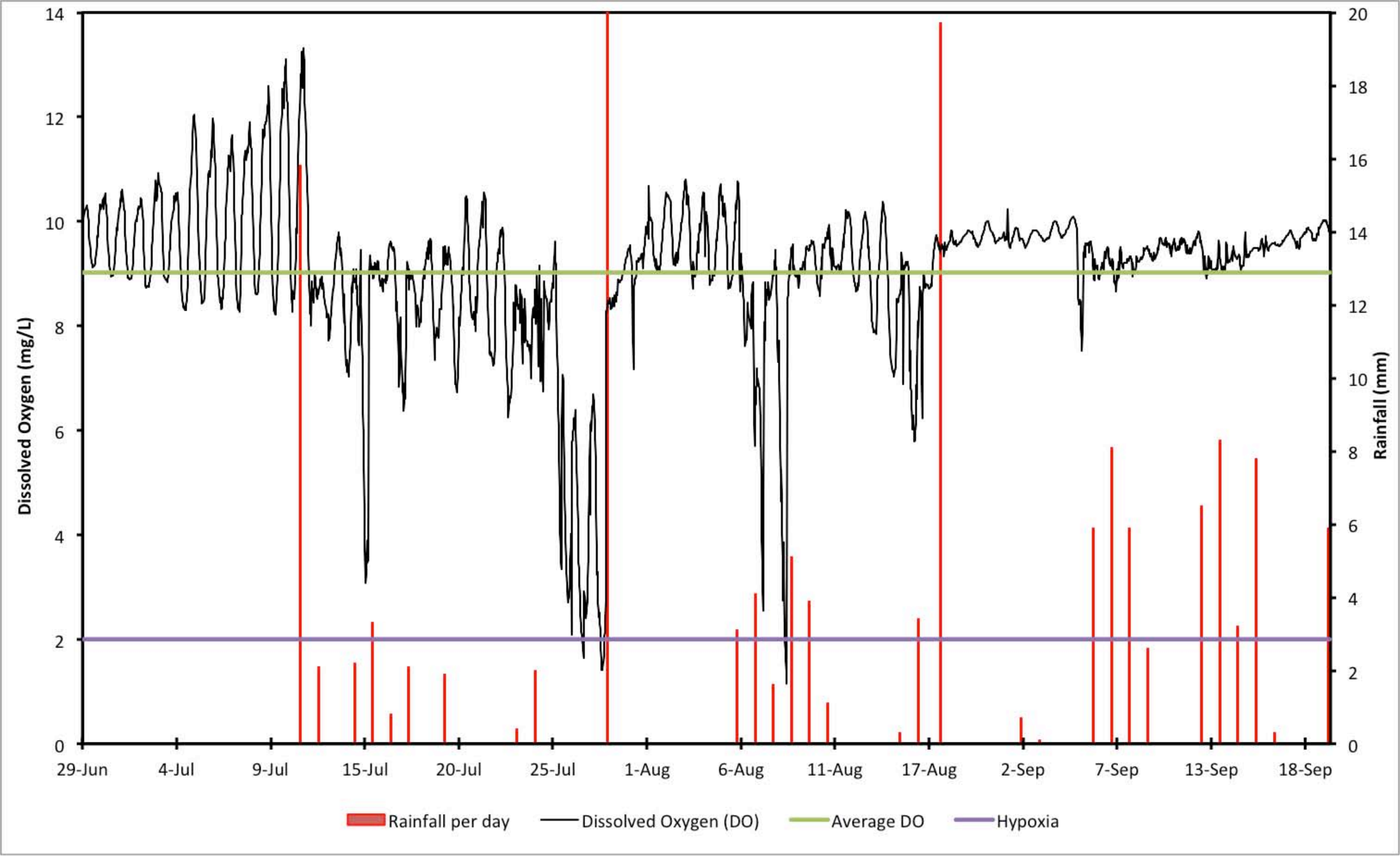
N
Vedenpuhdistamo
Vattenreningsverk
Hakuninmaa
Håkansåker
40
35
Present catchment border
New catchment border
Meters
0
100
200



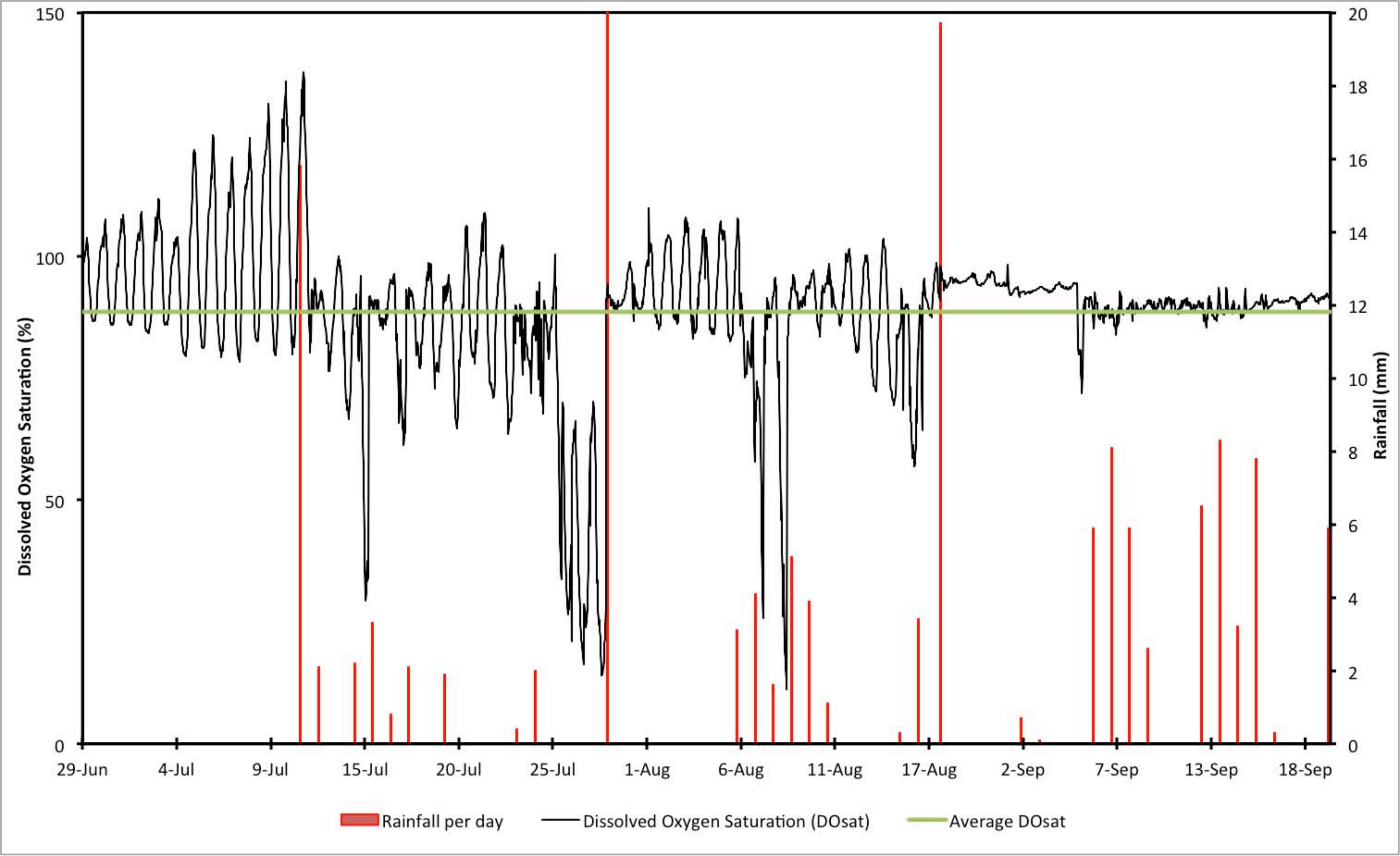
N
VANTAAN KAUPUNKI
HELSINGIN KAUPUNKI
FANNY CHURBERGIN KALLIO
VESILAITOS
KTY
AK
VENNYN PUISTO
TULEVA JOKERI II -TUNNELI
Present catchment border
New catchment border
Meters
0
100
200

Appendix 2 - Water quality charts

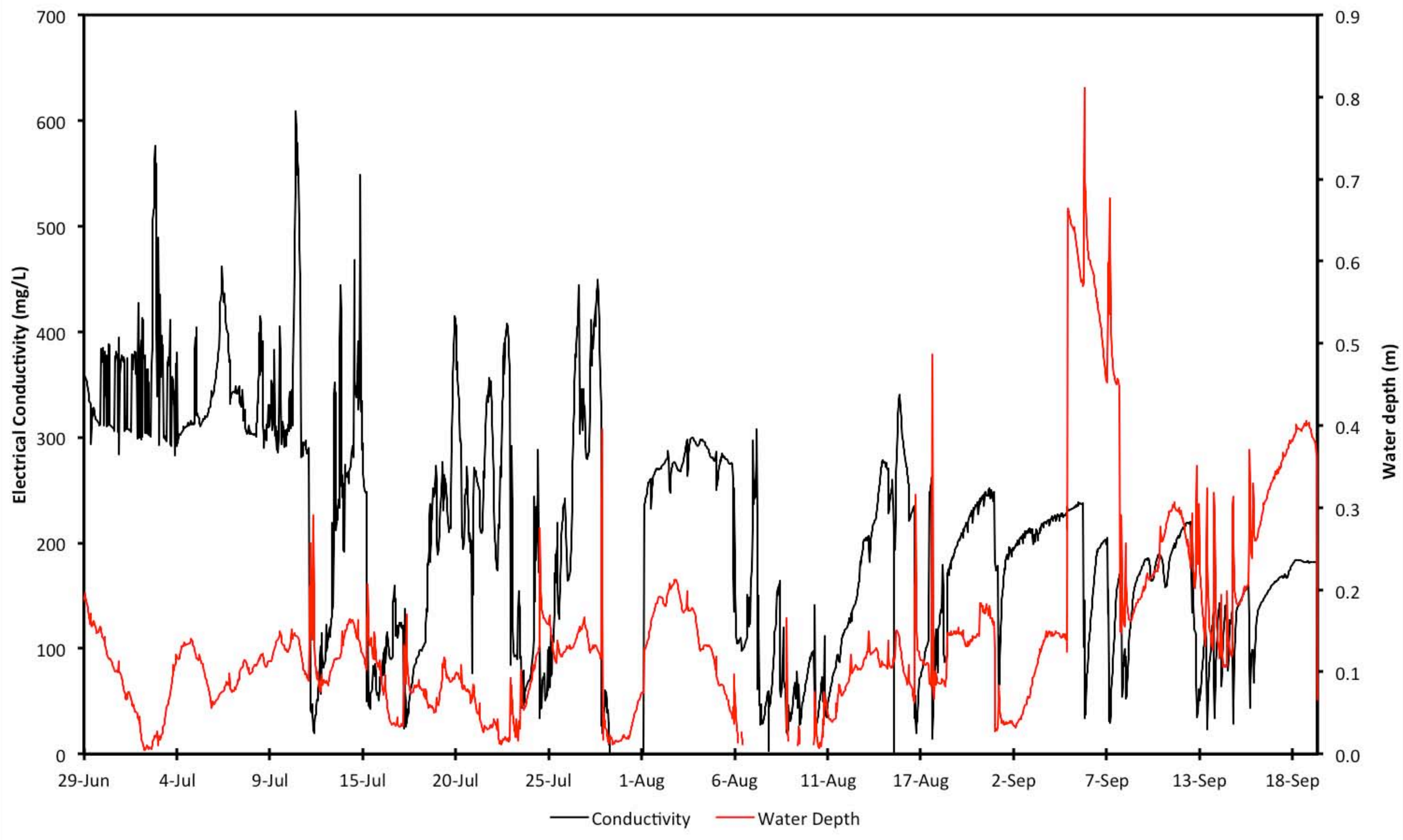




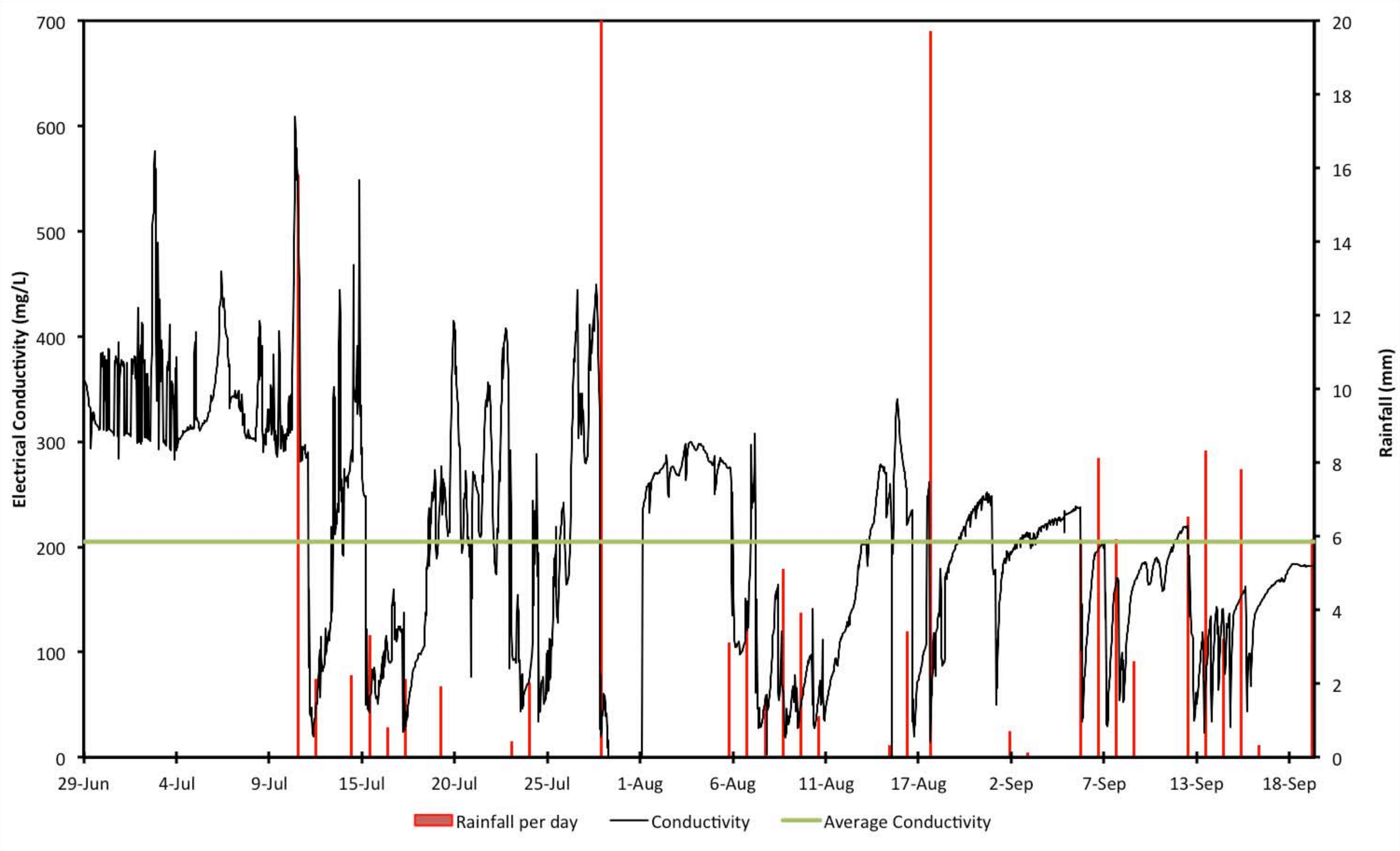
Dissolved Oxygen (mg/L)
Rainfall (mm)
0
2
4
6
8
10
12
14
16
18
20
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Dissolved Oxygen (DO)
Average DO
Hypoxia



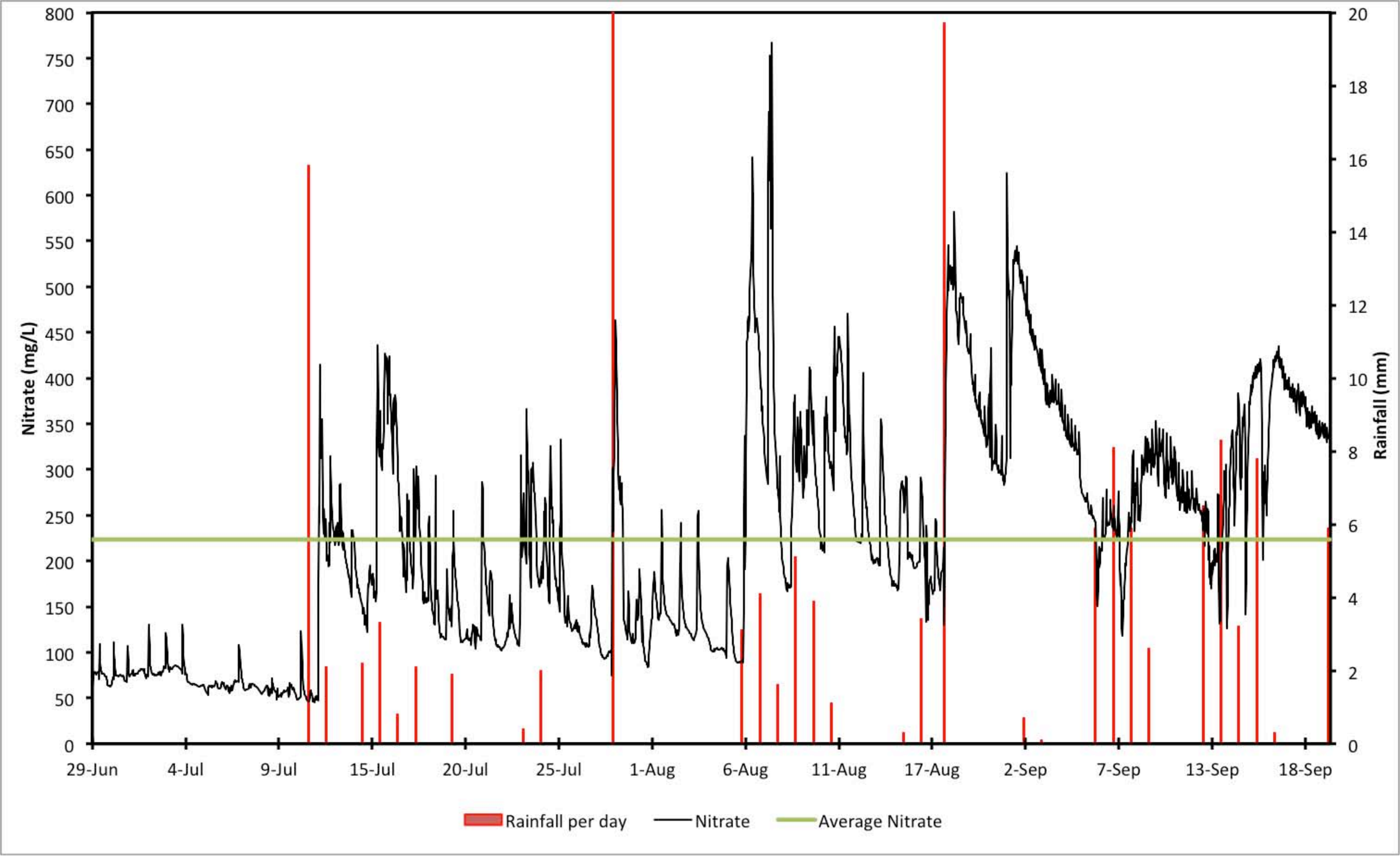
Dissolved Oxygen Saturation (%)
Rainfall (mm)
150
100
50
0
20
18
16
14
12
10
8
6
4
2
0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Dissolved Oxygen Saturation (DOsat)
Average DOsat



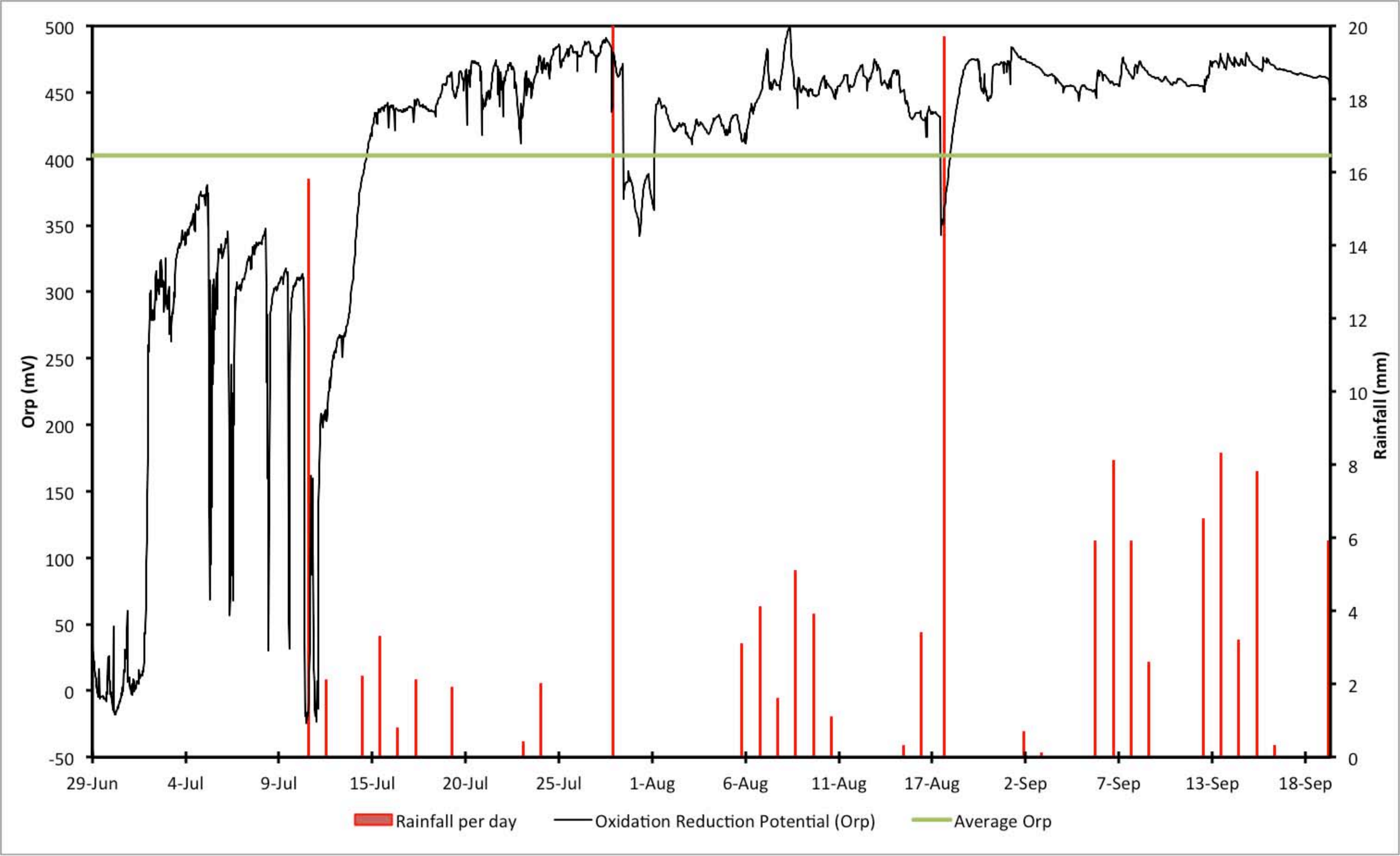
Electrical Conductivity (mg/L)
Water depth (m)
700
600
500
400
300
200
100
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Conductivity
Water Depth



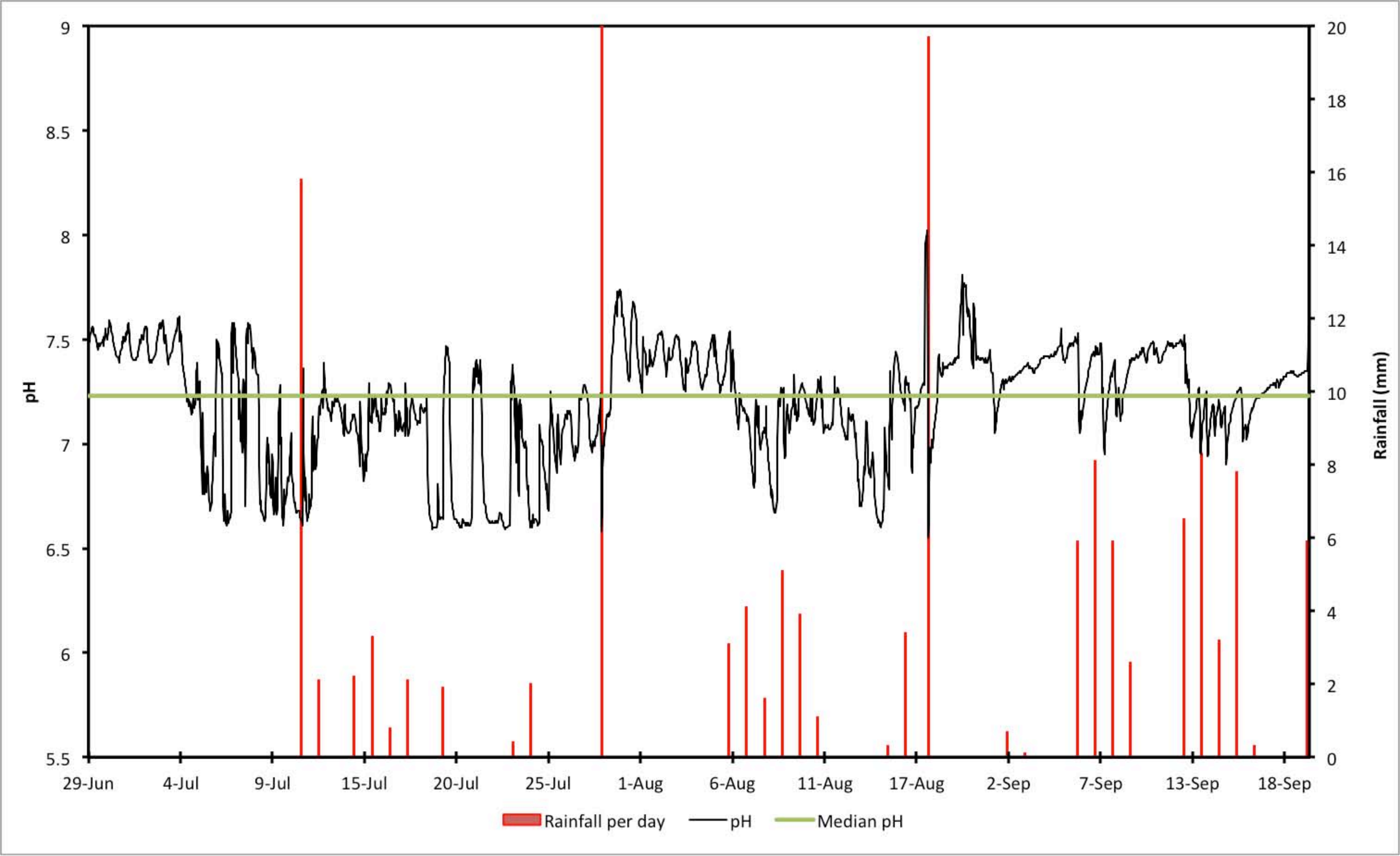
Electrical Conductivity (mg/L)
Rainfall (mm)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12
14
16
18
20
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Conductivity
Average Conductivity



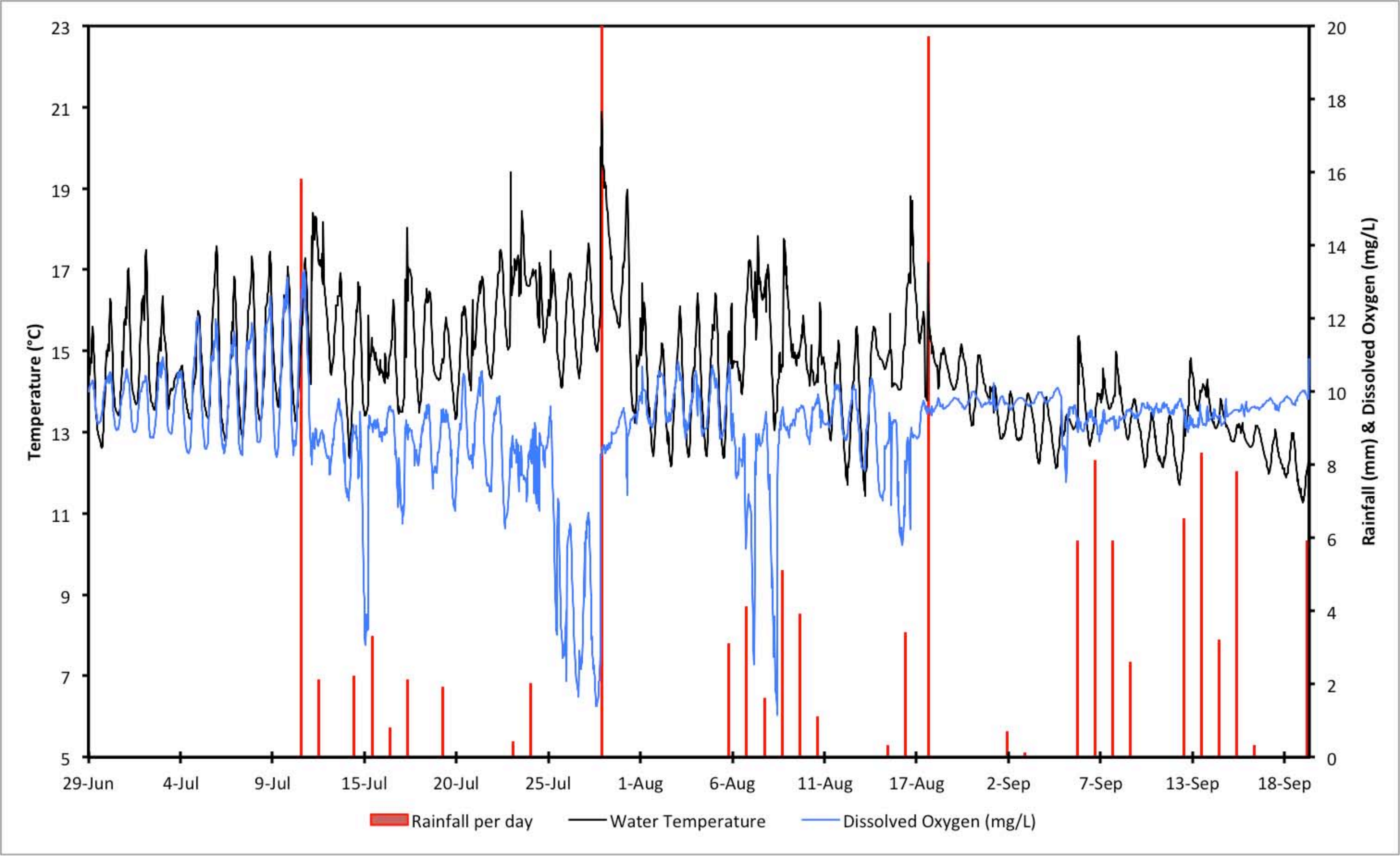
Nitrate (mg/L)
Rainfall (mm)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
20
18
16
14
12
10
8
6
4
2
0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Nitrate
Average Nitrate



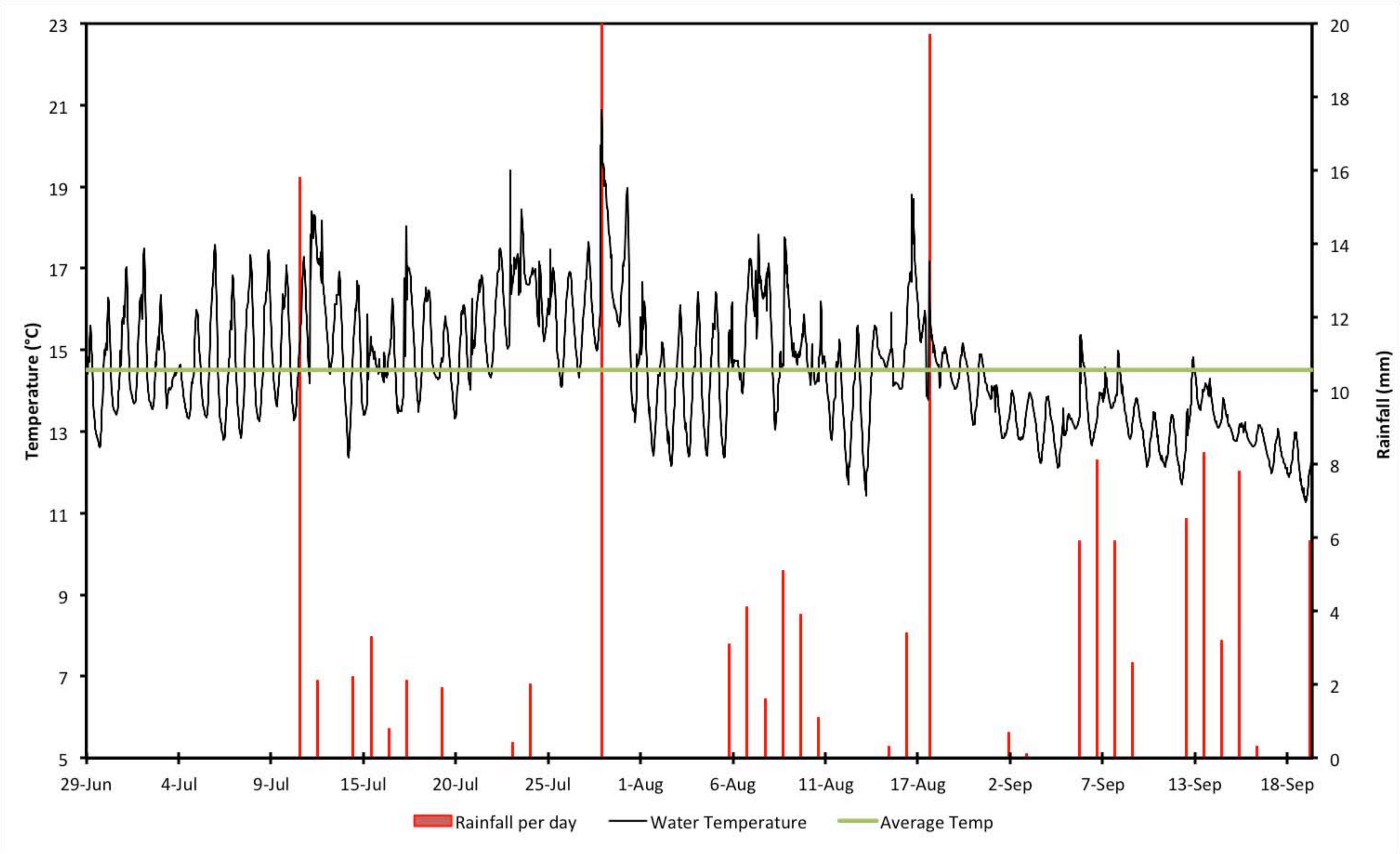
Orp (mV)
Rainfall (mm)
500
450
400
350
300
250
200
150
100
50
0
-50
20
18
16
14
12
10
8
6
4
2
0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Oxidation Reduction Potential (Orp)
Average Orp



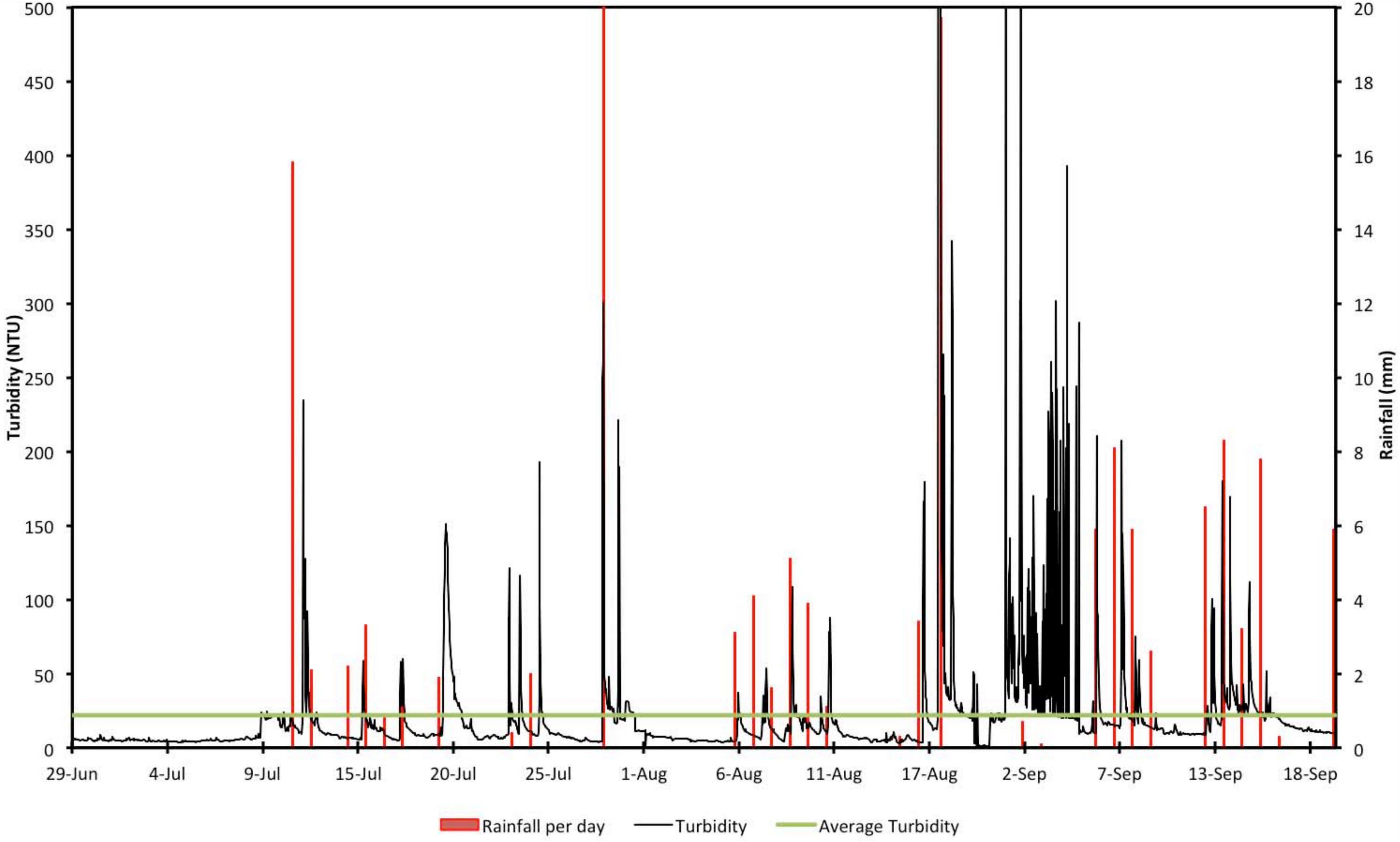
pH
Rainfall (mm)
9
8.5
8
7.5
7
6.5
6
5.5
20
18
16
14
12
10
8
6
4
2
0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
pH
Median pH



Temperature (°C)
Rainfall (mm) & Dissolved Oxygen (mg/L)
23
21
19
17
15
13
11
9
7
5
20
18
16
14
12
10
8
6
4
2
0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Water Temperature
Dissolved Oxygen (mg/L)

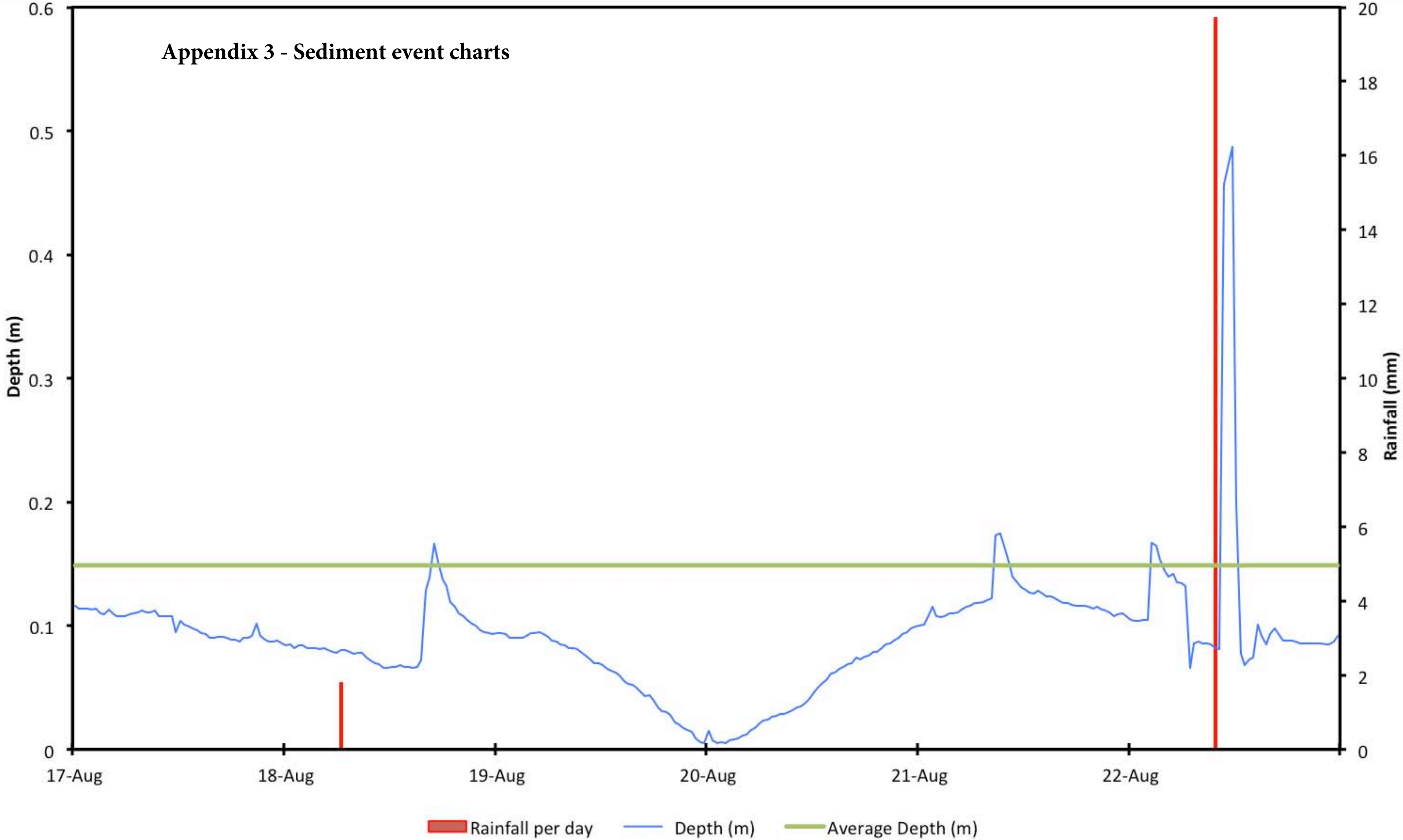


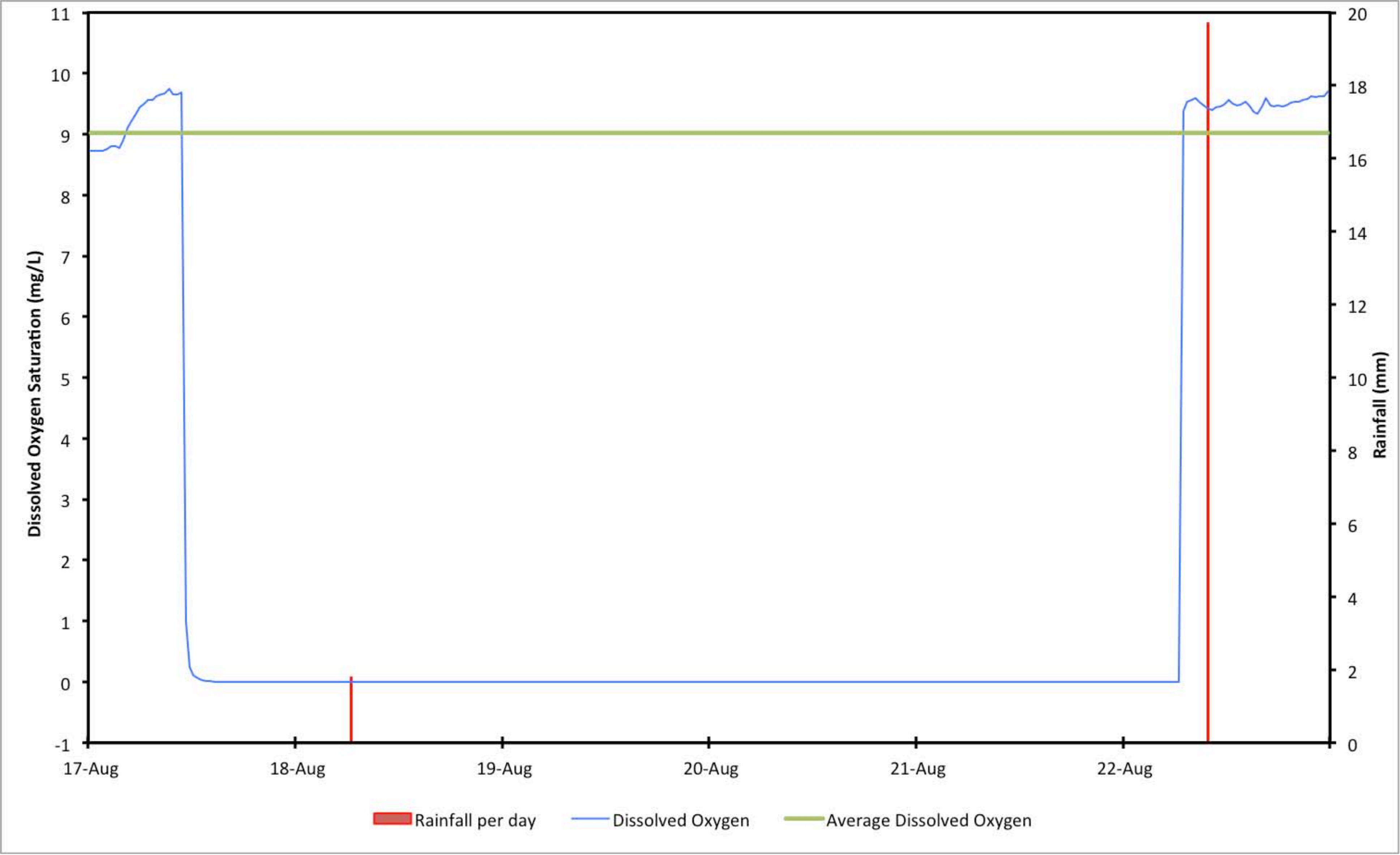
Temperature (°C)
Rainfall (mm)
23
21
19
17
15
13
11
9
7
5
20
18
16
14
12
10
8
6
4
2
0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Water Temperature
Average Temp



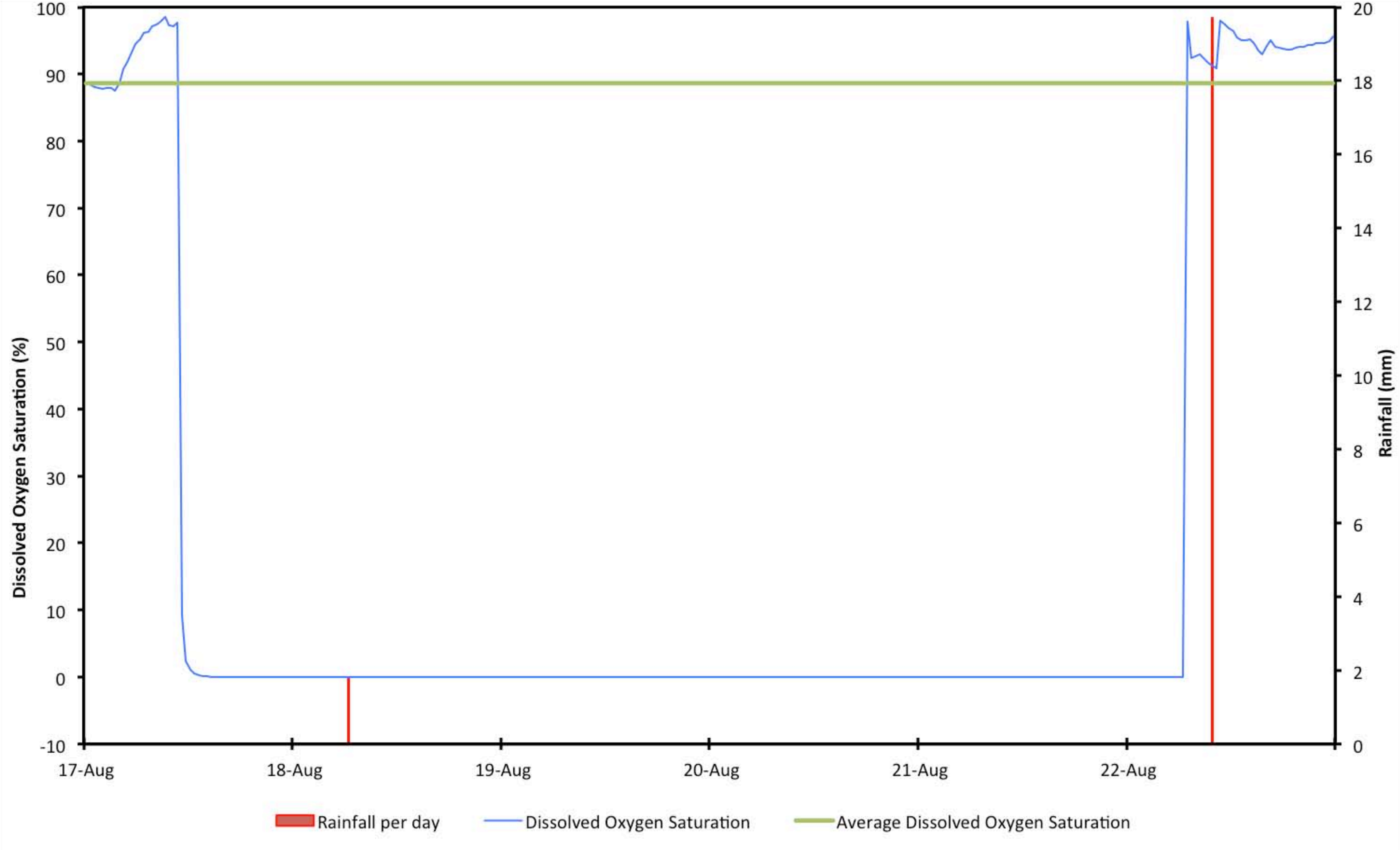
Turbidity (NTU)
Rainfall (mm)
500
450
400
350
300
250
200
150
100
50
0
20
18
16
14
12
10
8
6
4
2
0
29-Jun
4-Jul
9-Jul
15-Jul
20-Jul
25-Jul
1-Aug
6-Aug
11-Aug
17-Aug
2-Sep
7-Sep
13-Sep
18-Sep
Rainfall per day
Turbidity
Average Turbidity

Appendix 3 - Sediment event charts

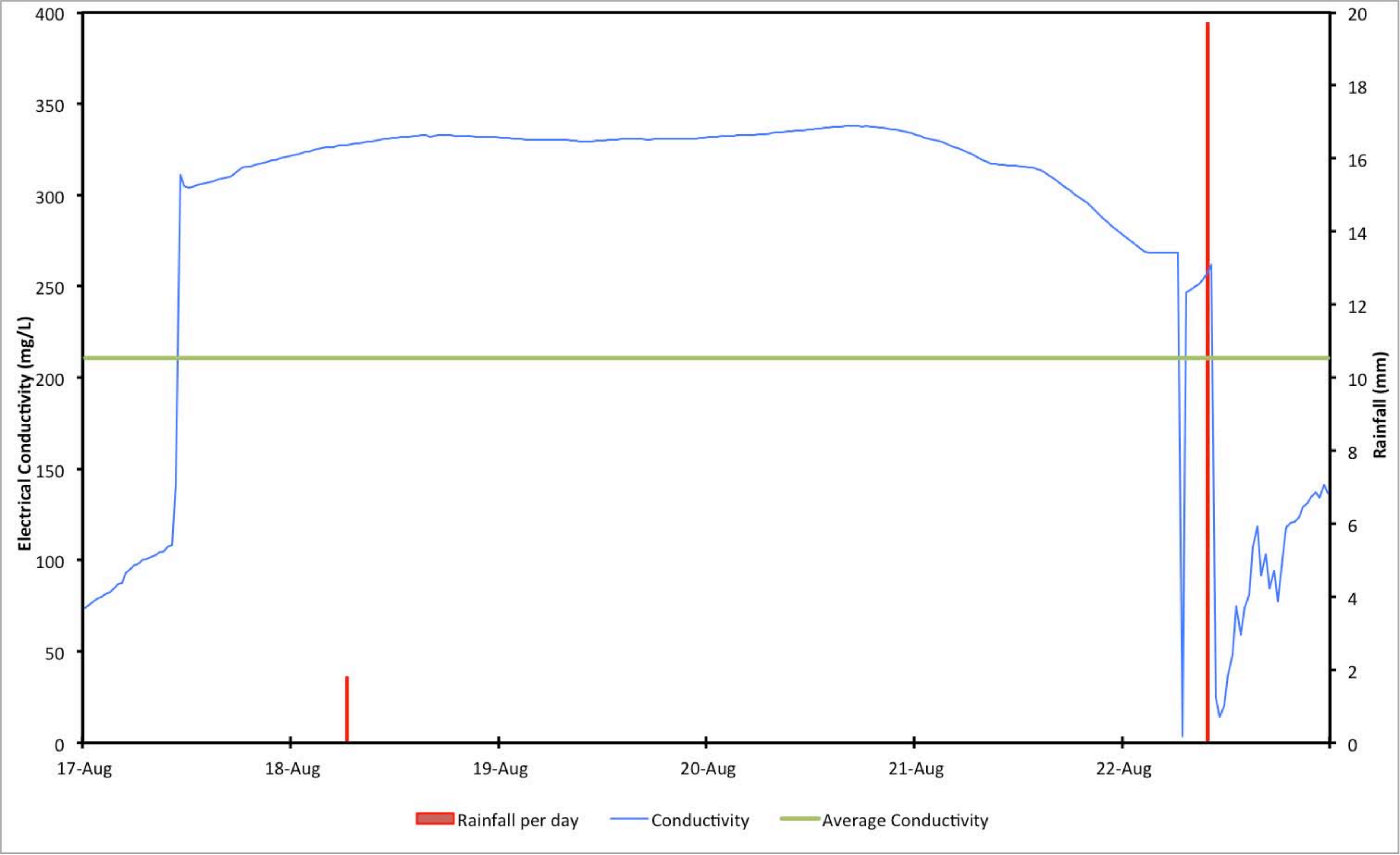




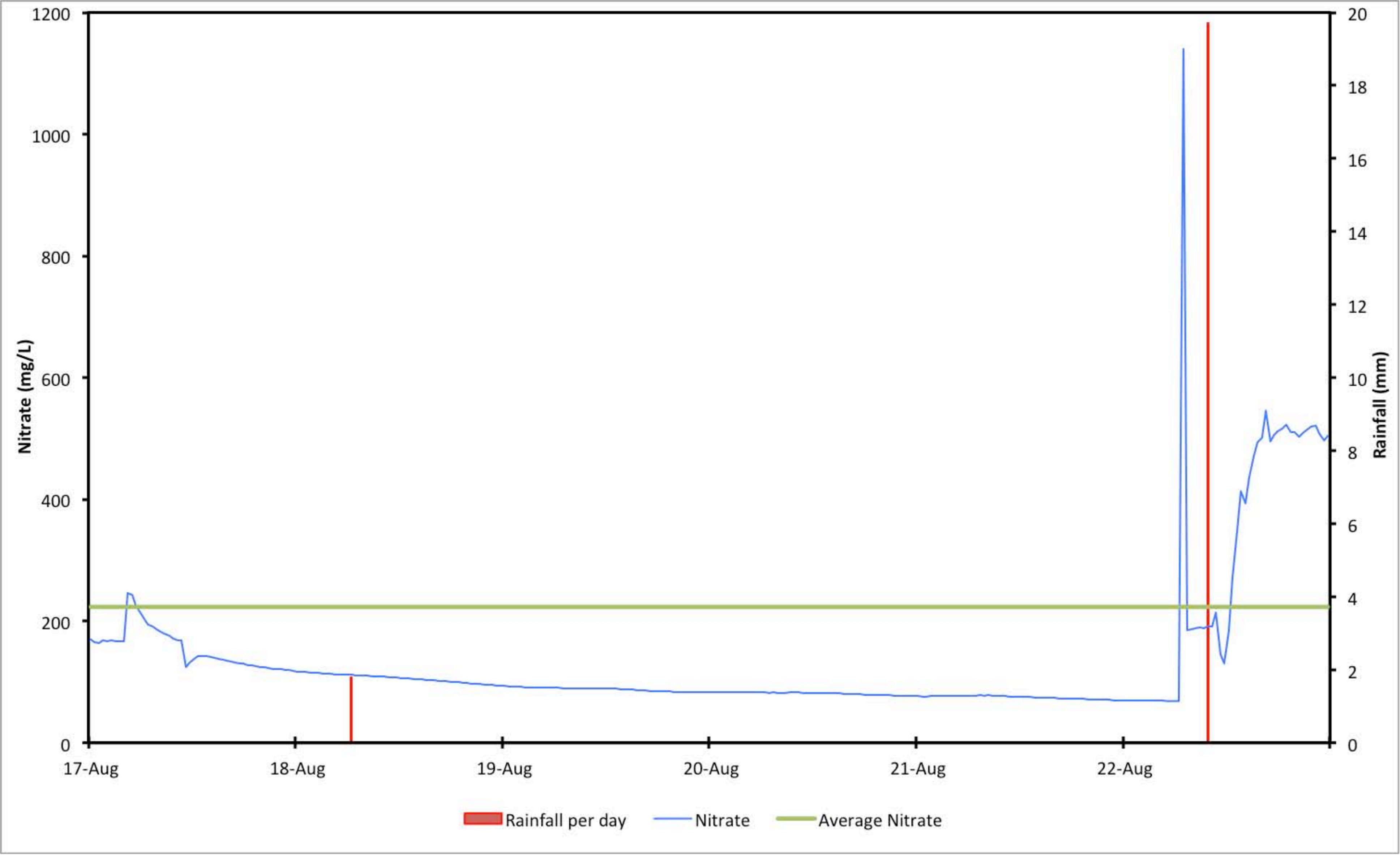
Dissolved Oxygen Saturation (mg/L)
Rainfall (mm)
11
10
9
8
7
6
5
4
3
2
1
0
-1
20
18
16
14
12
10
8
6
4
2
0
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
Rainfall per day
Dissolved Oxygen
Average Dissolved Oxygen

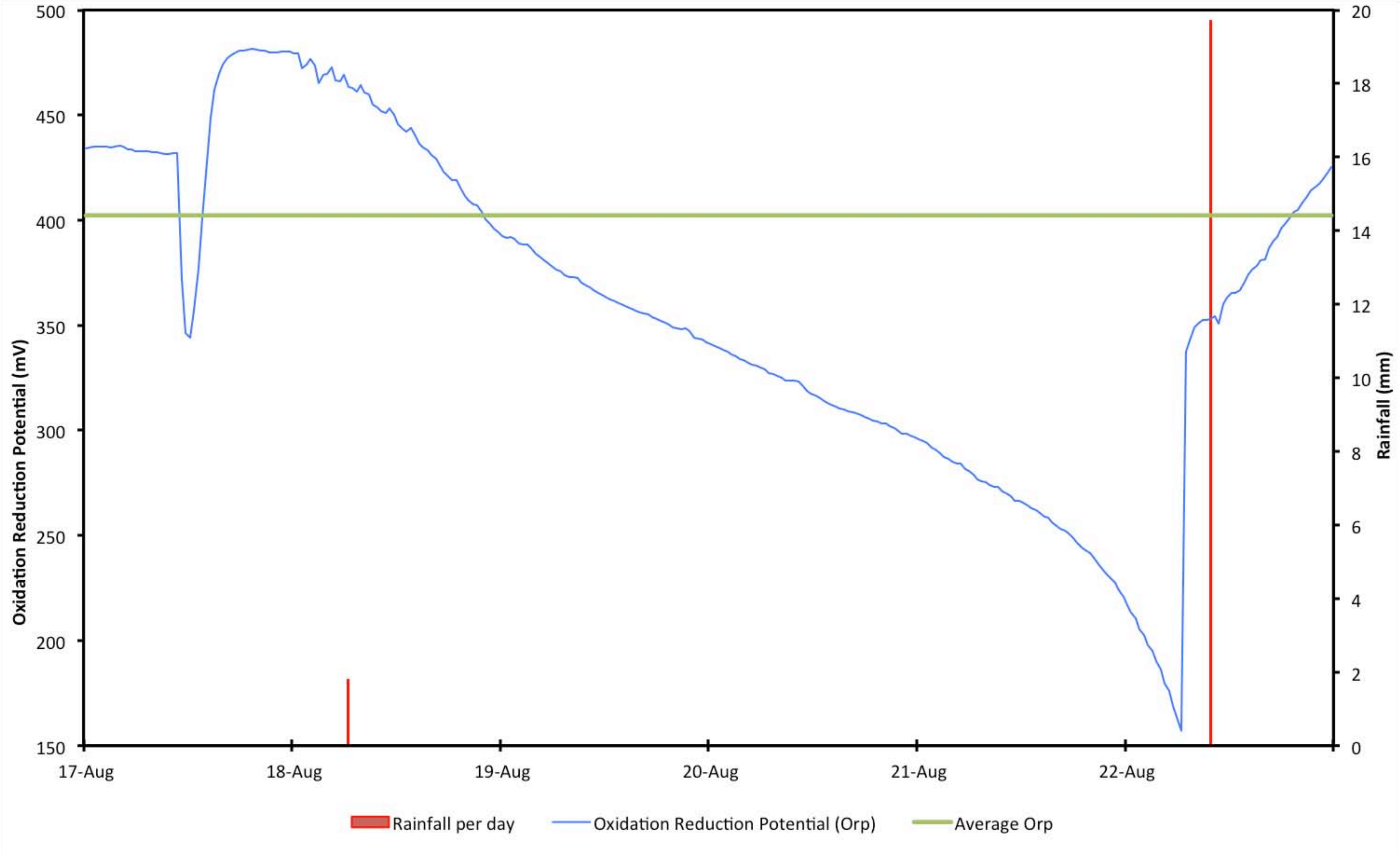


Dissolved Oxygen Saturation (%)
Rainfall (mm)
100
90
80
70
60
50
40
30
20
10
0
-10
20
18
16
14
12
10
8
6
4
2
0
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
Rainfall per day
Dissolved Oxygen Saturation
Average Dissolved Oxygen Saturation

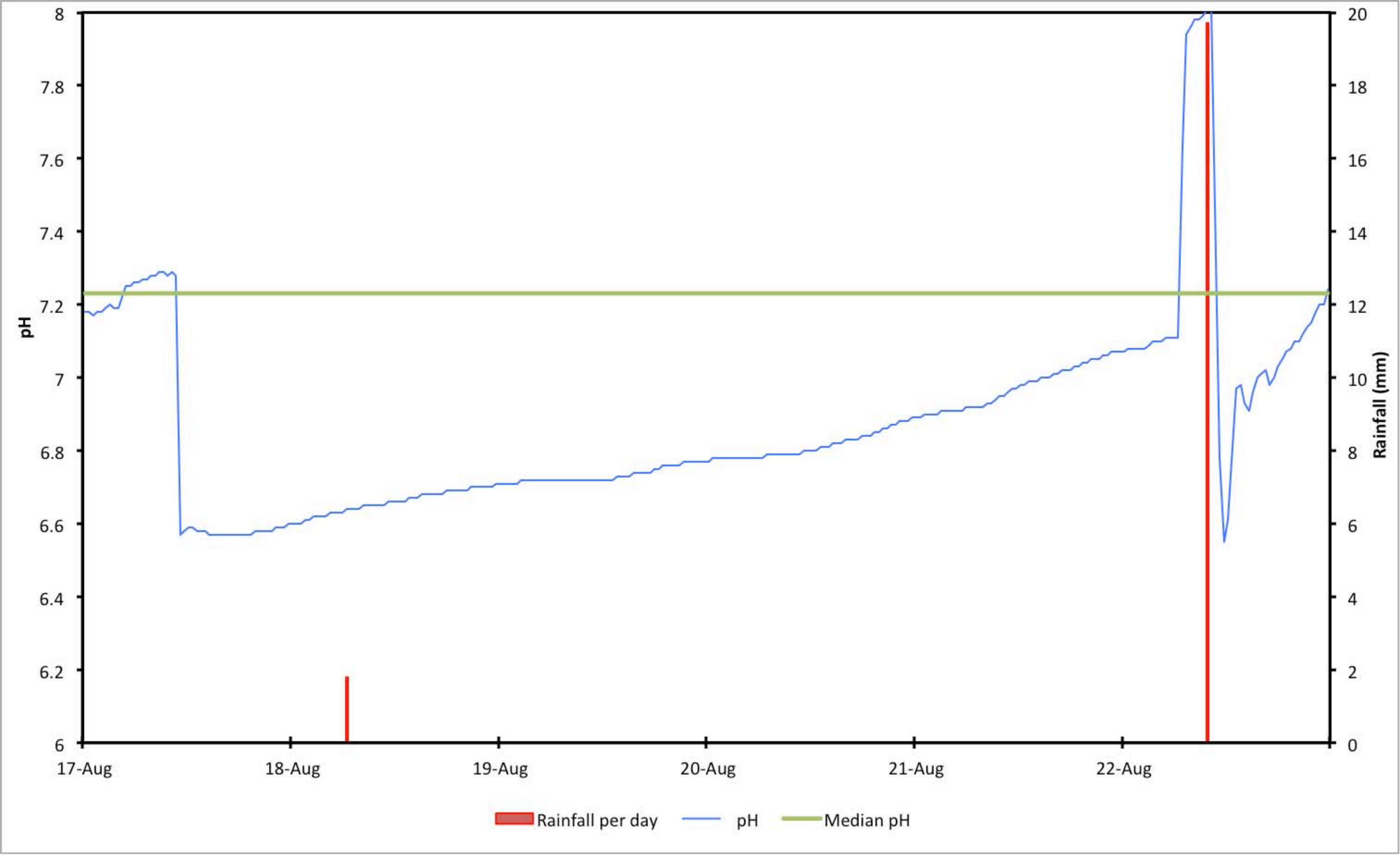


Electrical Conductivity (mg/L)
Rainfall (mm)
0
50
100
150
200
250
300
350
400
0
2
4
6
8
10
12
14
16
18
20
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
Rainfall per day
Conductivity
Average Conductivity

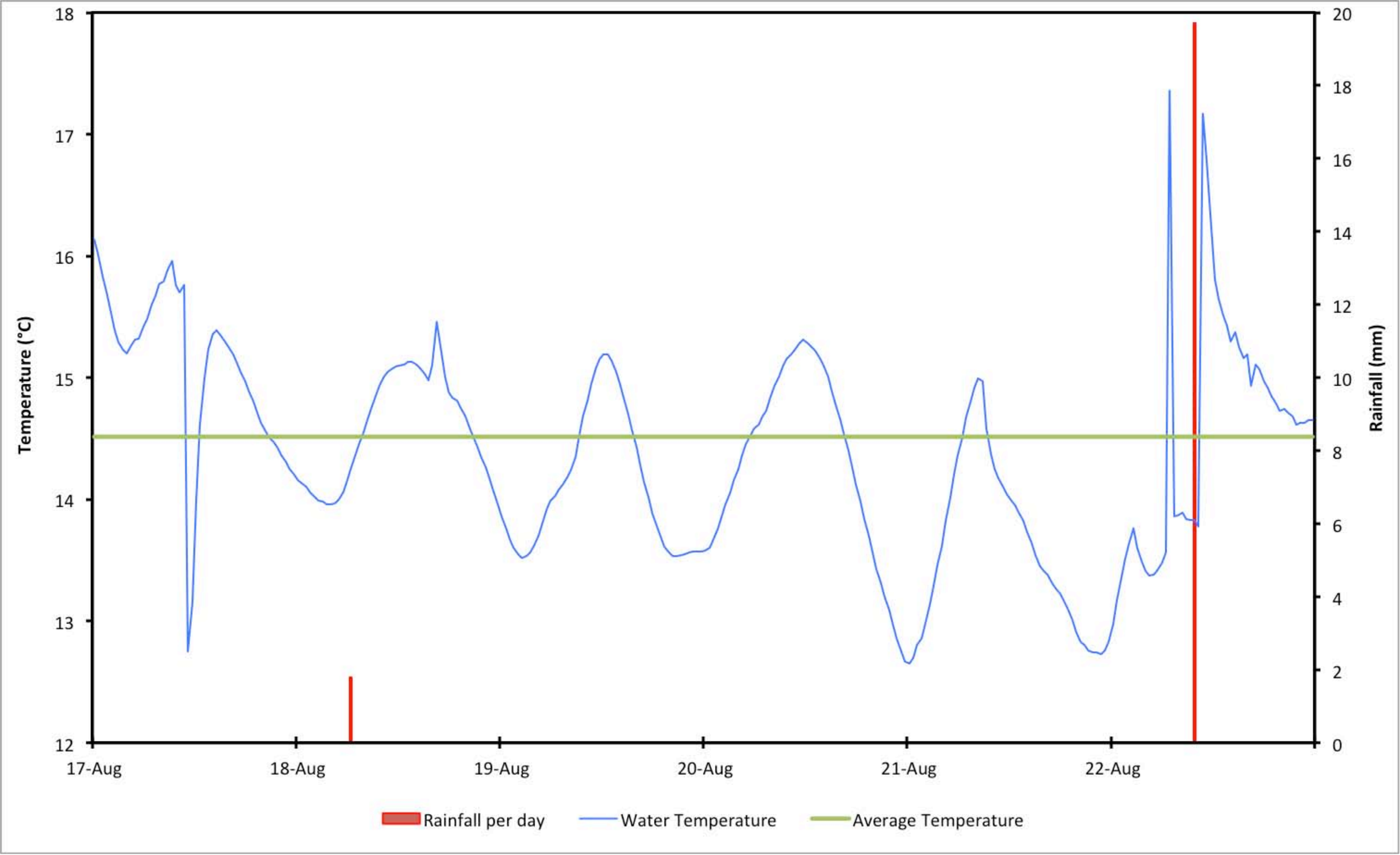

Nitrate (mg/L)
Rainfall (mm)
1200
1000
800
600
400
200
0
20
18
16
14
12
10
8
6
4
2
0
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
Rainfall per day
Nitrate
Average Nitrate



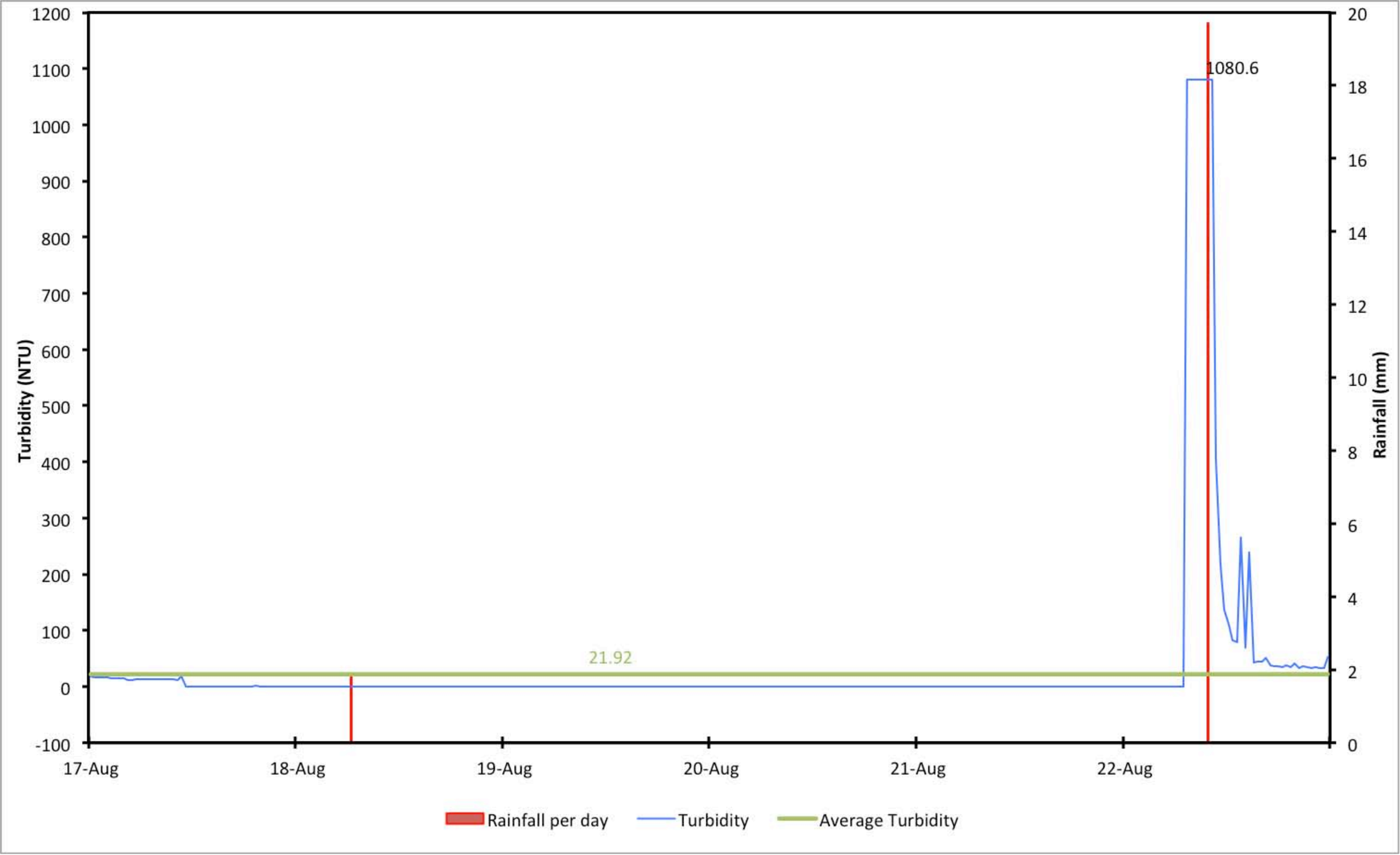
Oxidation Reduction Potential (mV)
Rainfall (mm)
500
450
400
350
300
250
200
150
20
18
16
14
12
10
8
6
4
2
0
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
Rainfall per day
Oxidation Reduction Potential (Orp)
Average Orp



pH
Rainfall (mm)
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
20
18
16
14
12
10
8
6
4
2
0
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
Rainfall per day
pH
Median pH



Temperature (°C)
Rainfall (mm)
18
17
16
15
14
13
12
20
18
16
14
12
10
8
6
4
2
0
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
Rainfall per day
Water Temperature
Average Temperature



Turbidity (NTU)
Rainfall (mm)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
20
18
16
14
12
10
8
6
4
2
0
17-Aug
18-Aug
19-Aug
20-Aug
21-Aug
22-Aug
1080.6
21.92
Rainfall per day
Turbidity
Average Turbidity

Appendix 4 - Land Use Categorised Imperviousness

Land use categories Total area m2

	Soil1Slope1	Soil1Slope2	Soil1Slope3	Soil2Slope1	Soil2Slope2	Soil2Slope3	Soil3Slope1	Soil3Slope2	Soil3Slope3	Total	% of catchment
Close small houses	0.00	50.30	285.33	8,455.37	2,666.91	13,425.70	8,960.74	802.54	11,904.66	**46,551.54**	3.48
Very close small houses	0.00	0.00	0.00	0.00	0.00	3,304.12	333.64	585.60	4,603.42	**8,826.78**	0.66
Rowhouses	0.00	0.00	0.00	1,244.27	1,171.58	5,998.00	1,401.10	1,792.33	11,729.44	**23,336.72**	1.74
Industrial	0.00	0.00	592.28	0.00	42.90	1,791.87	176.83	2,611.66	27,179.34	**32,394.88**	2.42
Forest	4,921.62	2,808.86	38,103.60	56,476.19	32,042.48	297,197.30	82,864.21	39,170.40	415,069.10	**968,653.77**	72.41
Gravel	0.00	0.00	3,497.99	840.27	481.53	4,046.76	884.40	532.31	8,574.60	**18,857.85**	1.41
Lawn	0.00	72.64	494.01	7,162.72	2,864.01	17,580.39	7,956.04	2,375.17	23,377.43	**61,882.40**	4.63
Roads	529.77	644.50	8,606.20	11,078.53	6,715.63	38,338.75	13,684.78	7,279.26	77,457.60	**164,335.01**	12.29
Water	10.07	89.90	336.67	326.85	119.79	3,057.21	1,090.31	944.11	6,872.68	**12,847.60**	0.96
Total area m2	**5,461.46**	**3,666.20**	**51,916.07**	**85,584.19**	**46,104.83**	**384,740.10**	**117,352.05**	**56,093.38**	**586,768.27**	**1,337,686.55**	**100.00**
	0.41	0.27	3.88	6.40	3.45	28.76	8.77	4.19	43.86	100.00	

Land use categories as a % of total catchment area

Slope/Gradient	0-1°			1-4°			>4°			
Soil category	A	B	C	A	B	C	A	B	C	Total area (%)
Close small houses	0.0%	0.6%	0.7%	0.0%	0.2%	0.1%	0.0%	1.0%	0.9%	3.5%
Very close small houses	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.3%	0.5%
Row houses/small block houses/well-spaced block houses	0.0%	0.1%	0.1%	0.0%	0.1%	0.1%	0.0%	0.4%	0.9%	1.7%
Close block houses, industrial & transport areas, schools	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.1%	2.0%	2.3%
Forest	0.4%	4.2%	6.2%	0.2%	2.4%	2.9%	2.8%	22.2%	31.0%	72.3%
Transport areas - asphalt	0.0%	0.8%	1.0%	0.0%	0.5%	0.5%	0.6%	2.9%	5.8%	12.1%
Transport areas - gravel	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.3%	0.3%	0.6%	1.4%
Field, meadow, lawn	0.0%	0.5%	0.6%	0.0%	0.2%	0.2%	0.0%	1.3%	1.7%	4.5%
Water	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%	0.2%	0.5%	0.9%
Soil area %	0.4%	6.3%	8.8%	0.2%	3.4%	4.1%	3.7%	28.6%	43.7%	

Area weighted runoff as % from total area of each land use

Slope/Gradient	0-1°			1-4°			>4°			
Soil category	A	B	C	A	B	C	A	B	C	Average runoff coefficient for each land use
Close small houses	0.00%	2.72%	3.85%	0.02%	1.15%	0.43%	0.12%	7.21%	7.67%	**0.23**
Very close small houses	0.00%	0.00%	0.94%	0.00%	0.00%	1.99%	0.00%	11.23%	18.25%	**0.32**
Row houses/small block houses/well-spaced block houses	0.00%	1.60%	2.40%	0.00%	2.01%	3.84%	0.00%	12.85%	30.16%	**0.53**
Close block houses, industrial & transport areas, schools	0.00%	0.00%	0.27%	0.00%	0.07%	4.84%	0.91%	3.32%	58.73%	**0.68**
Forest	0.01%	0.29%	0.86%	0.01%	0.33%	0.81%	0.39%	6.14%	10.71%	**0.20**
Transport areas - asphalt	0.00%	1.34%	1.41%	0.00%	1.02%	1.13%	9.27%	10.73%	22.73%	**0.48**
Transport areas - gravel	0.00%	1.16%	1.93%	0.02%	1.16%	1.34%	0.24%	11.36%	18.89%	**0.36**
Field, meadow, lawn	0.23%	4.72%	5.83%	0.31%	3.27%	3.54%	4.71%	21.00%	42.42%	**0.86**
Water	0.08%	2.54%	8.49%	0.70%	0.93%	7.35%	2.62%	23.80%	53.49%	**1.00**

Breakdown of % rainfall converted to runoff from each category

Slope/Gradient	0-1°			1-4°			>4°			
Soil category	A	B	C	A	B	C	A	B	C	
Close small houses	0.00%	11.76%	16.61%	0.07%	4.94%	1.86%	0.53%	31.12%	33.11%	100.00%
Very close small houses	0.00%	0.00%	2.91%	0.00%	0.00%	6.14%	0.00%	34.64%	56.31%	100.00%
Row houses/small block houses/well-spaced block houses	0.00%	3.03%	4.54%	0.00%	3.80%	7.27%	0.00%	24.31%	57.05%	100.00%
Close block houses, industrial & transport areas, schools	0.00%	0.00%	0.40%	0.00%	0.10%	7.10%	1.34%	4.87%	86.19%	100.00%
Forest	0.03%	1.49%	4.38%	0.07%	1.69%	4.14%	2.01%	31.39%	54.80%	100.00%
Transport areas - asphalt	0.00%	2.81%	2.95%	0.00%	2.14%	2.37%	19.47%	22.53%	47.73%	100.00%
Transport areas - gravel	0.00%	3.21%	5.34%	0.05%	3.21%	3.72%	0.66%	31.48%	52.33%	100.00%
Field, meadow, lawn	0.26%	5.49%	6.78%	0.36%	3.80%	4.12%	5.48%	24.41%	49.31%	100.00%
Water	0.08%	2.54%	8.49%	0.70%	0.93%	7.35%	2.62%	23.80%	53.49%	100.00%